

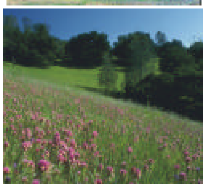

Report to Congress

on

Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research

Prepared by

U.S. Department of Energy
Office of Nuclear Energy,
Science, and Technology

January 2003

EXECUTIVE SUMMARY

This report has been prepared by the U.S. Department of Energy (DOE) to respond to Congressional direction contained in Conference Report accompanying the Energy and Water Appropriations Act of 2002 (House Report 107-258)[1]. In that report, Congress instructed the Department to provide answers to several questions related to the agency's spent fuel separations and transmutation research activities. Specifically, Congress directed the Department to:

1) *Compare chemical and pyroprocessing, accelerator-driven transmutation, and fast reactor transmutation alternatives, including full disclosure of all waste streams;*

2) *Estimate the life cycle costs to construct, operate, and decommission and decontaminate all necessary facilities;*

3) *Compare the proliferation resistance of the various technologies;*

4) *Provide a strategy for siting new processing and disposal facilities that would be required for the various reprocessing and transmutation alternatives;*

5) *Use the once-through fuel cycle as presently used in the United States and the amount of spent nuclear fuel presently scheduled for disposal in the geologic repository as the baseline for all comparisons; and*

6) *Present the Department's strategy for siting the new processing and disposal facilities that would be required for the various processing and transmutation alternatives, assuming a capacity sufficient to process the amount of spent fuel presently scheduled for geologic disposal.*

This report is the U.S. Department of Energy's response to the Congressional directive. It reflects strategies and approaches developed with the advice and input of the Nuclear Energy Research Advisory Committee (NERAC) Subcommittee on Advanced Nuclear Transformation Technology (ANTT), chaired by Nobel Laureate Dr. Burton Richter.

The information presented in this report reflects the current state of the research and development knowledge on separations and transmutation technologies. While research conducted thus far by the Department and its collaborators overseas provides a basis from which some information may be derived, the Department found, in the course of attempting to respond to the questions posed by Congress, that the research is at far too early a stage to enable a meaningful or relevant response to many of the questions. Although significant progress has been made since DOE embarked on this area of work, the knowledge base, particularly with regard to life-cycle cost is limited. It is therefore important to note that the Department can only provide preliminary answers or best estimates for the questions at this time.

Additional research would be required to provide a full understanding of the answers to questions about advanced fuel cycle technologies such as are posed by Congress, and the following report provides an overview of the type of research that would be needed. Therefore, we provide the

1 The exact language of the directive is contained in this report as Appendix A.

following direct responses, based on the work conducted in preparing this report, to the issues above:

Issue 1: *Compare chemical and pyroprocessing, accelerator-driven transmutation, and fast reactor transmutation alternatives, including disclosure of all waste streams*BThe Department is sufficiently familiar with these technologies to provide a concept-level comparison of the alternatives; however, limited detail is available on issues such as costs and waste streams. As discussed in the report, the primary path for chemical spent fuel treatment, a process called “Uranium Extraction Plus” (UREX+), is still at a conceptual stage of development. Transmutation systems, which are largely the province of the Department=s Generation IV activities, are similarly at the very early stages of development. The information that is available regarding spent fuel processing alternatives may be found on pages II-2 through II-4 and III-4 through III-7; information regarding transmutation systems may be found on II-5 and III-7 through III-10.

Issue 2: *Estimate the life cycle costs to construct, operate, and decommission and decontaminate all necessary facilities*–No precise information on the costs of needed facilities exists today. The development of meaningful cost estimates will be a major task inherent in any future research.

Issue 3: *Compare the proliferation resistance of the various technologies*BNo metrics yet exist to provide a meaningful comparison of proliferation resistance. The Department is working with the international community to develop an agreed framework of proliferation metrics, but these are not expected to become available for at least another year or so after the issuance of this report. However, the report does highlight proliferation issues associated with spent fuel disposition on page II-6, and discusses the proliferation-resistance of advanced fuel cycle technologies on pages II-2 through II-3 and II-6.

Issue 4: *Provide a strategy for siting new processing and disposal facilities that would be required for the various reprocessing and transmutation alternatives*BThis question cannot be answered until the technologies to be employed have been selected and the necessary environmental impacts studied. This report is unable to address siting issues.

Issue 5: *Use the once-through fuel cycle as presently used in the United States and the amount of spent nuclear fuel presently scheduled for disposal in the geologic repository as the baseline for all comparisons***B**This approach is reflected in the report. For example, as highlighted in Section I, the current once-through fuel cycle produces spent nuclear fuel that requires approximately 300,000 years to decay to the toxicity level of uranium ore. If the research suggested by the report should prove successful, application of advanced fuel cycle technologies would produce waste forms that would decay to that level after only about 1,000 years.

Issue 6: *Present the Department's strategy for siting the new processing and disposal facilities that would be required for the various processing and transmutation alternatives, assuming a capacity sufficient to process the amount of spent fuel presently scheduled for geologic disposal***B**Clearly, as outlined in the report, the research is in far too early a stage to anticipate the siting of specific facilities. However, the Department anticipates that any advanced fuel cycle facilities built in the United States would be constructed and operated by the private sector with appropriate incentives that reflect the national benefits of implementing technology approaches to managing nuclear wastes.

Continued research on the management of spent nuclear fuel is important to help the United States and other nations continue and expand the use of nuclear energy. While many countries are conducting advanced research and development on this topic, it is important for the United States to take a leadership role to ensure that advanced proliferation-resistant technologies become an integrated part of the management of spent nuclear fuel.

These technologies could reduce the cost of waste disposal and also provide other benefits such as enhancing national security by significantly reducing the inventories of commercially generated plutonium in spent fuel.

As discussed in the main text of this document, research thus far points to two elements of an Advanced Fuel Cycle Initiative (AFCI) that could be conducted in parallel as part of an integrated effort. The two elements of the research consist of an intermediate-term technology, referred to as AFCI Series One, which emphasizes advanced technologies applied to current reactor technology, and a long-term technology, referred to as AFCI Series Two, which could provide for complete resolution of radiotoxicity and heat load issues.

AFCI Series One would address the intermediate-term issues associated with spent nuclear fuel, specifically reducing the volume of material requiring geologic disposition by extracting the uranium (which represents 96 percent of the constituents of spent nuclear fuel), and reducing the proliferation risk through the destruction of significant quantities of plutonium contained in spent nuclear fuel. These technologies could be deployed as a part of the current infrastructure and be used in concert with current and future light water reactor plants in the United States. Deployment of these technologies could occur in a time frame that would permit enhancement of the planned repository at Yucca Mountain.

AFCI Series Two would address long-term issues associated with spent nuclear fuel, specifically the development of fuel cycle technologies that could sharply reduce the long-term radiotoxicity and long-term heat load of high-level waste sent to a geologic repository. Because implementing these technologies would also require the successful deployment of Generation IV nuclear energy systems, this technology should be considered a longer-term option. If successful, this technology could enable the commercial waste stored in a repository to be no more toxic than natural uranium ore after approximately 1,000 years — thereby augmenting the performance of geological disposal of nuclear wastes beyond what is now possible. Moreover, success in this area would provide a very long-term, sustainable fuel supply for expanded use of nuclear power — one that could last hundreds of years.

As described in the following report, these two elements are not independent. The objectives of advanced fuel cycle research can only be met if AFCI Series Two technologies and Generation IV nuclear energy systems are successfully developed. However, AFCI Series Two requires AFCI Series One to be practical — Series One technologies would be needed to deal with the large volumes of radioactive materials in spent fuel.

The following report provides a discussion of the issues and technologies involved in advanced fuel cycle research and charts a course for their exploration.

I. PROGRAM OVERVIEW

The Administration has concluded, as reflected in the *National Energy Policy*, that nuclear energy can play a strong role in the future of the Nation's energy security needs. Nuclear power is the only technology available that can produce economic, baseload quantities of energy without emitting harmful pollutants including those associated with global climate change. Nuclear power plants produce about a fifth of all U.S. electric power and do so in an economic, safe, and reliable fashion.

Although nuclear energy does not emit harmful pollutants, it generates spent nuclear fuel. Disposal of this material, which is highly toxic for hundreds of thousands of years, presents a wide range of social, political, regulatory, and technical issues.

Over the last three years, DOE, its laboratories, and university and private company partners have worked with the international research community to explore the potential of advanced nuclear technologies that can reduce the difficulty of disposing of spent nuclear fuel from nuclear power plants. This research, conducted under DOE's Advanced Accelerator Applications (AAA) Program (the program that the Advanced Fuel Cycle Initiative, or AFCI, will replace), is designed to reduce the volume and toxicity of the nuclear waste. This report is based on the knowledge gained during that research and the results of deliberations with many experts around the world.

***Why Treat and Transmute Spent Fuel*?**

The AFCI Program and related efforts in other countries are designed to find the most effective technologies to accomplish three basic steps in spent fuel treatment:

1) **Reduce Spent Fuel Volume** by creating a final high-level waste form that is lower in volume than the original spent fuel,

2) **Separate Long-Lived, Highly Toxic Elements** (*i.e.*, actinides such as plutonium and americium) that present the most difficult disposition challenge, and

3) **Reclaim Spent Fuel's Valuable Energy** by providing a method to reclaim the energy value contained in the highly toxic spent fuel elements while providing for their destruction.

Accomplishing these steps requires the use of complex chemical and nuclear reaction processes that can be conducted in a manner that is safe, cost effective, environmentally friendly, and proliferation-resistant. The next two sections of this document will report on DOE's efforts thus far in exploring the different technical approaches to spent fuel treatment and transmutation and outline the steps that could be considered for further development of these technologies.

It is important to recognize that even with the most ambitious goals for this research, DOE does not expect that any future spent fuel treatment and transmutation technologies will obviate the need for a geologic repository. DOE believes, however, that in the long term, it may be possible to apply advanced nuclear technologies to reduce both the cost and difficulty of operating a geologic repository and the technical need to build multiple repositories in the future. Doing so could help reduce one of the main long-term barriers to the expanded use of nuclear energy.

In addition to the benefits spent fuel treatment and transmutation technology could provide in terms of significantly reducing the need for a second repository, it may someday enable us to reduce the toxicity of spent fuel placed in the first geologic repository. By destroying the most toxic, long-lived radioactive components of the spent fuel, it may be possible to reduce significantly the time it takes for the commercial nuclear waste in a repository to decay to the toxicity of natural uranium ore by a factor of 300. Again, while a deep geologic repository is still needed, this technology can optimize its cost and technical performance.

This report supersedes the report DOE prepared on the subject of Accelerator Transmutation of Waste in 1999. That earlier document estimated the cost of a program to develop and deploy a system of high-energy accelerator-based spent fuel treatment facilities to deal with all U.S. commercial spent fuel. Because that report examined only the deployment of accelerator-based facilities, DOE believes it was not based on a realistic approach to transmutation and is, therefore, no longer relevant to our consideration of transmutation. As indicated by the Secretary of Energy in a hearing before the House Appropriations Subcommittee on Energy and Water on March 6, 2002, this accelerator-only approach to transmutation could cost the United States as much as $280 billion to implement.

More recent estimates, such as those performed by the Organization for Economic Cooperation and Development (OECD), suggest that employing spent fuel treatment and transmutation on a commercial scale would add at least ten percent to the overall cost of electricity. While this analysis is based on scenarios that apply to both accelerator facilities and reactor facilities, in DOE's view, this analysis is too reliant on existing spent fuel treatment and transmutation technologies. We believe that any future role for these technologies will require the use of far more efficient and cost-effective technological approaches, and it is simply too early to estimate accurately the costs of spent fuel treatment and transmutation. This document describes the research program that will be required to enable an informed estimate of the potential benefits and costs of spent fuel treatment and transmutation technology.

Similarly, it is far too early to rely on this emerging technology to plan for the future. For this reason, DOE believes that all analyses regarding the future of nuclear power in the United States should assume the continued use of current fuel cycle technology and the application of a deep geologic repository early in the next decade. While we recommend no change in current planning at this time, we do recognize that if nuclear power continues to operate in this country for the long term[1] it will continue to produce significant quantities of spent nuclear fuel. This fact presents long-term challenges that must be addressed.

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[1]Even if no new nuclear power plants are constructed in the United States, the vast majority of existing plants can be expected to remain in operation into the 2030s.

The Nuclear Waste Challenge

Today, the United States has 44,000 metric tonnes (Mt) of spent nuclear fuel residing at commercial nuclear power plants and generates approximately 2,000 Mt of additional spent fuel each year. At this growth rate, the statutory limit for the planned geologic repository, 63,000 Mt of civilian nuclear spent fuel, will be reached by 2015 (see Figure I-1).

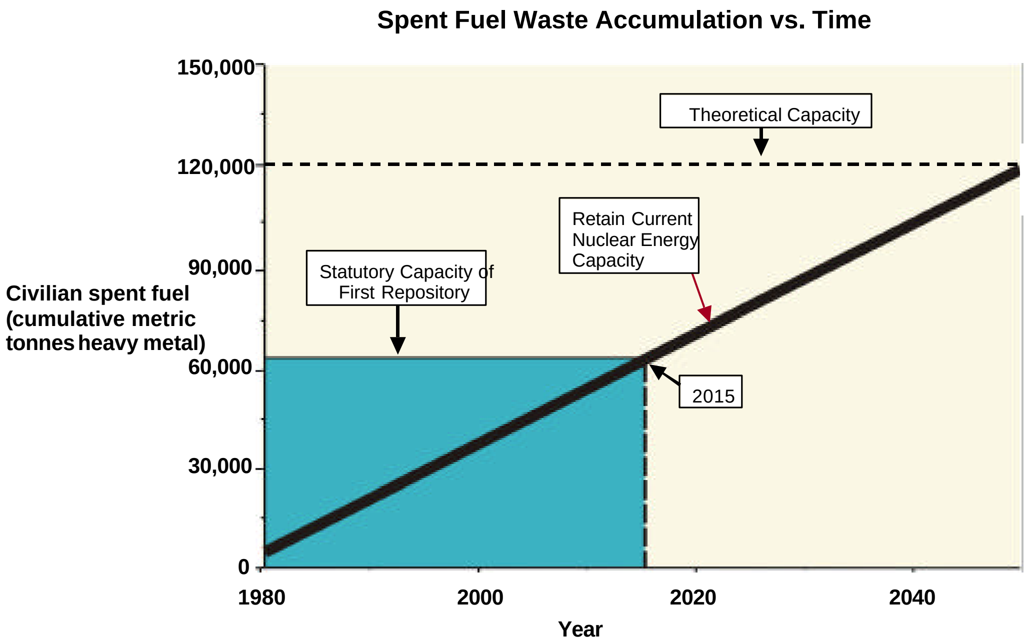


Figure I-1

As a result, the quantity of spent fuel produced by nuclear power plants may become a long-term challenge to the possibility of building new nuclear power plants as anticipated by the *National Energy Policy*. While nuclear plants produce far less waste by volume than any comparable energy-producing or industrial activity, the unique nature of spent fuel requires that dealing with this waste product be considered as part of the long-term planning for the use of nuclear power. The volume of high-level waste requiring disposal has a direct impact on the ultimate cost of a geologic repository. As more waste is sent to a repository, more emplacement tunnels (or "drifts") are required. Nonetheless, in the wake of September 11, 2001, it is far more desirable to move the Nation's spent nuclear fuel to a centralized, underground location than to allow it to remain at 130 locations across the country.

Another factor to be considered is that after several decades out-of-reactor, spent fuel can serve as a convenient reservoir for plutonium. Figure I-2 shows that hundreds of tons of plutonium have accumulated in commercial spent fuel in the United States. With the decay, as a function of time, of the fission products that make the handling of spent fuel difficult and expensive, this

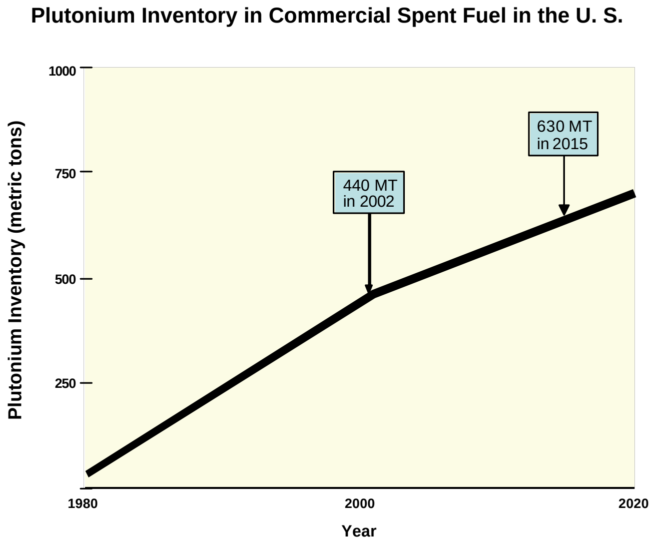


Figure I- 2

material could be retrieved from a repository in 50 to 100 years and used to create separated plutonium. The United States has become increasingly concerned with the global accumulation of plutonium and believes that it presents an important proliferation issue worldwide.

While spent fuel in the United States does not present a proliferation risk, only a third of the world's nuclear power plants are in the United States. Developing technologies to address this long-term threat would be in the interest of the Nation's security.

Finally, in the long-term future, the world will find that uranium, like oil or natural gas, is not an infinite resource. Expert organizations such as the World Nuclear Association project that between 2050 and 2080, nuclear power plants worldwide will encounter a serious shortage in the uranium needed to produce nuclear fuel.

A very recent, highly-detailed analysis performed by the industry consultancy, Energy Resources International (ERI), indicates that this vulnerability could appear even sooner under certain scenarios. As shown in Figure I-3, ERI projects that currently-known world uranium resources (including both miner and government stockpiles such as Russian highly enriched uranium) may be depleted in the coming decades to a level that could only provide about half of the annual requirements projected for 2030, assuming that nuclear fuel demand does not grow during the next few decades. This assumes that most of the already-mined uranium (excess HEU and government inventories) is largely consumed by about 2030. However, if world nuclear power grows by only 50 percent by 2030, then uranium production would have to almost triple to meet requirements. While it is generally expected that some new production resources will be found over the coming decades, this analysis demonstrates that nuclear fuel from mined uranium could become a serious restraint on the growth potential of nuclear power in the not-too-distant future.

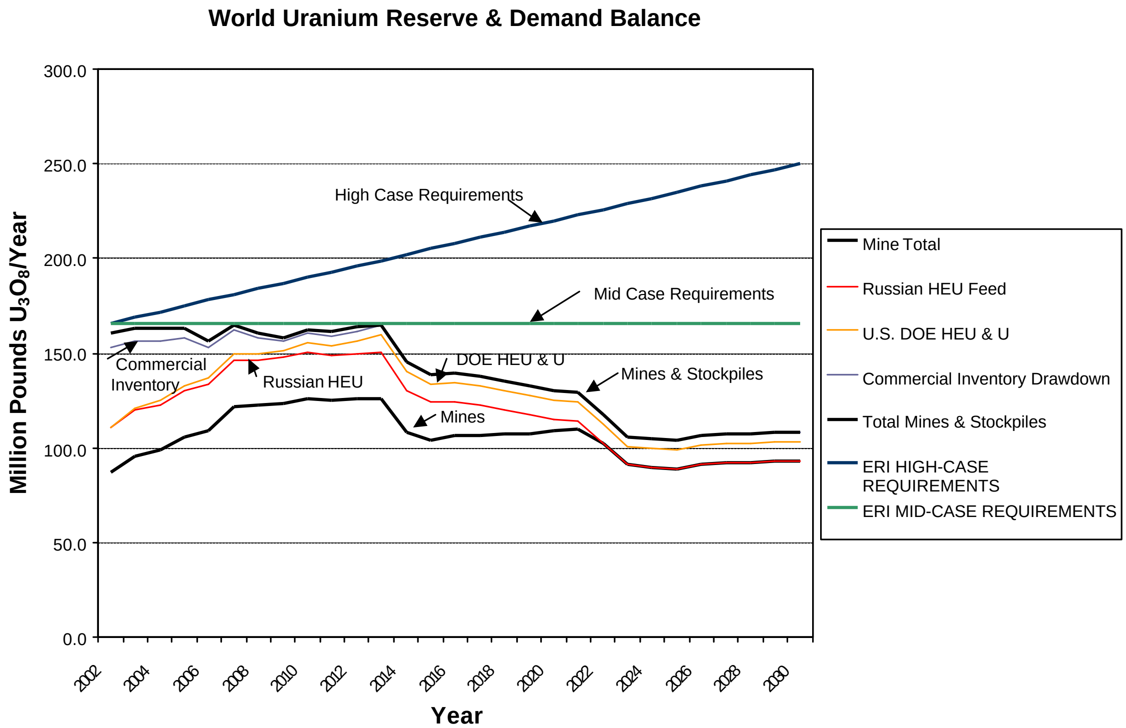


Figure I-3

If the *Nuclear Power 2010* initiative announced by the Secretary of Energy is successful, the United States will have nuclear plants in operation until at least 2070. As a result, research into technologies that can make the most efficient use of our nuclear fuel resources will support the Nation's long-term energy independence. Moreover, the 44,000 Mt of spent nuclear fuel currently stored at nuclear power plant sites across the country contain the energy equivalent to more than 6 billion barrels of oil or about two full years of U.S. oil imports. This issue, therefore, has significant energy security implications.

DOE's Integrated Nuclear Research Approach

DOE has embarked upon a program of research and development that can address the numerous issues facing the future of nuclear energy. In 2001, the United States and eight other countries established the Generation IV International Forum (GIF) to create a common, international nuclear research and development agenda for the future (currently 10 countries are GIF members). Working in conjunction with NERAC, the GIF has developed the *Generation IV Technology Roadmap.* The *Roadmap* identifies a half-dozen nuclear energy systems that the GIF has concluded can best provide major enhancements to the use of nuclear energy–meeting aggressive goals[2] for economic performance, resistance to proliferation and terrorism, sustainability, and safety and reliability. If successful, this work could lead to next-generation energy sources that could produce electricity, hydrogen, and process heat economically at costs

[2]The Generation IV technology goals were drafted by the NERAC and reviewed and adopted by the 10-country GIF. These goals have been accepted by organizations of the international research community, including the OECD, the International Atomic Energy Agency, and EURATOM.

competitive with any other energy alternative. More than a hundred scientists and engineers from all over the world have been engaged in this enterprise and the United States is now holding discussions with its partners to proceed with joint research in selected areas of mutual interest.

The *Roadmap* is designed to consider entire nuclear systems - not just reactor technologies but fuel cycle technologies as well. Since much work has been completed under the AAA Program, the information thereby developed will be used to inform the final results of the *Roadmap*. The *Roadmap* will, in turn, inform future AFCI Program activities.

The Department conducted detailed system analysis studies on various nuclear energy systems that now inform its choices for a future research agenda. These studies, which included significant and invaluable input from NERAC, examined approaches–with and without the use of accelerator driven systems–to transmute the Nation's spent nuclear fuel. These options were designed to point the way toward enhanced methods of spent fuel management that enabled the Nation to optimize its repository program while obtaining additional energy from material that would otherwise be disposed of in a repository.

In the area of spent fuel treatment, the AAA Program led the development of advanced, environmentally responsible, proliferation-resistant aqueous separations technologies (Uranium Extraction technology, or "UREX" and UREX+). In FY 2002, initial analytical results from the hot UREX experiments carried out at the Savannah River Technology Center during August 2002, uranium recovery from actual spent light water reactor (LWR) fuel exceeded 99.9% and in the runs, the contamination of the uranium products was below current Nuclear Regulatory Commission regulations for Class C waste. This successful demonstration implies that uranium from spent LWR fuel could be stored, used, or disposed of as a non high-level waste (*i.e.* class C low-level waste).

With the results from both programs in hand thus far, it is clear that part of the long-term research agenda will include fast reactor systems (*i.e.*, reactors that produce very high energy neutrons) working in concert with some form of advanced, proliferation-resistant spent fuel treatment. Technologies capable of destroying even very small quantities of highly toxic, long-lived radioactive species in nuclear waste, such as accelerator-based systems, may also play a prominent role in these considerations.

Work completed by the AAA Program and the Generation IV Nuclear Energy Systems Initiative has enabled DOE to identify clearly the goals and approach for research that could enable DOE, Congress, and industry to make an informed decision about the potential of advanced fuel cycle technologies. Addressing issues associated with managing high-level nuclear wastes will–in both the intermediate and long terms–drive the consideration of future research. In summary, the intermediate-term issues are:

- reducing high-level waste volumes,
- increasing the capacity of the planned geologic repository,

- reducing the technical need for a second repository,
- reducing long-term inventories of plutonium in spent fuel, and
- enabling recovery of the energy contained in spent fuel;

and the long-term issues are:

- reducing the toxicity of spent nuclear fuel,
- reducing the long-term heat generation of spent nuclear fuel,
- providing a sustainable fuel source for nuclear energy, and
- supporting the future operation of Generation IV nuclear energy systems.

With this more precise definition of the program's technology objectives (made possible by the work and analyses completed by the AAA Program and the Generation IV effort), DOE believes that the AAA Program could now be succeeded by a more complete and focused effort – the AFCI. AFCI will develop advanced, proliferation-resistant technologies to treat and transmute spent nuclear fuel. It would consist of two major elements:

- **AFCI Series One–**This component of the program would address the intermediate-term issues associated with spent nuclear fuel, primarily by reducing the volume and heat generation of material requiring geologic disposition. Doing so would support the Nation's first repository and reduce the technical need for additional repositories (about which the Department must make a recommendation between 2007 and 2010). This area of work would include exploration of proliferation-resistant processes and fuels that could enable the destruction of significant quantities of commercially generated plutonium in LWRs or high temperature gas-cooled reactors.

- **AFCI Series Two–**This component of the program would address the long-term issues associated with spent nuclear fuel. Specifically, this effort would explore fuel cycle technologies that could sharply reduce the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository, and support development of potential Generation IV fuel cycles.

It is important to note that AFCI Series One and AFCI Series Two are complementary and, as a result, would be managed in tandem as part of a multi-phased effort to develop advanced spent fuel treatment and transmutation technologies. For example, treatment technologies that emerge from AFCI Series One may prove to be invaluable front-end steps to more advanced processes targeted in AFCI Series Two. Integrating these technology programs would be essential to the success of the overall effort.

Even under the most successful scenario for this research, it will be necessary to proceed with all practical speed toward the establishment of a deep geologic repository to contain U.S. spent nuclear fuel and high-level radioactive wastes. Even if new treatment and transmutation fuel facilities are deployed in agreement with the aggressive schedule outlined above, it will be necessary to maintain spent fuel in a safe, terrorist-proof, environmentally-responsible location for an extended period until all the fuel can be treated. Further, the outputs of transmutation, while theoretically far less toxic and toxic for a far shorter period of time than spent nuclear fuel, will still be highly radioactive for hundreds of (and likely a thousand) years. For these reasons, it makes eminent sense to proceed with the Department's geologic repository project, while maintaining the expectation that AFCI may yet significantly reduce the cost of geologic disposal while increasing its safety and proliferation-resistance.

The DOE Approach to Management of the AFCI Program

During the past three years, the AAA Program has developed a strong set of engineering and management teams at the national laboratories and with industry to develop the technology plans and experiments needed to address AFCI issues. These research and development teams include more than 300 scientists and technicians at various national laboratories and sites and the University of Nevada, Las Vegas (UNLV).

DOE will continue to seek advice on the AFCI Program from the chartered subcommittee of NERAC chaired by Nobel Laureate Burton Richter. This subcommittee provides ongoing, expert advice regarding the program's technical and scientific goals and has most recently provided DOE with invaluable guidance associated with evaluating and eliminating the technical options that will form AFCI. In particular, the subcommittee's expert advice has been essential in broadening the focus of DOE's research activity from an accelerator-only focused effort to a more balanced program. As envisioned by the subcommittee, accelerator-driven systems could have an important role in a "final burn" that could be needed to enable the program to meet its toxicity reduction goals.

A major element of the AAA Program's approach to achieving its mission in all phases has been a robust cooperative program with international partners interested in the development of this technology. To date, DOE has entered into two formal agreements for cooperative efforts with other nations to pursue these technology areas and has obtained over $100 million worth of analytical and experimental data. DOE will continue to exchange information with these international partners and will explore the potential for similar cooperation with other countries. In addition, at their 2002 summit meeting, Presidents Bush and Putin ordered their governments to prepare joint studies to outline areas of potential future cooperation on advanced, proliferation-resistant fuel cycle technologies. DOE's interaction with Russia verifies that that nation would prove a valuable partner in the U.S. AFCI Program. Russian scientists have explored a wide range of advanced fuel cycle technologies that are of considerable interest and continue to operate facilities that would be important to a future, cooperative research effort if the policy issues that currently prevent such cooperation from proceeding are cleared away.

Nonproliferation Policy Issues

In addition to international policy issues, the United States would need to consider its domestic policies with regard to spent fuel treatment and transmutation. While pursuing these technologies is within the purview of the Department of Energy, deploying advanced, proliferation-resistant spent fuel treatment and transmutation technologies would require a review and, where necessary, update of existing U.S. policies. As stated in the recommendations of the *National Energy Policy:*

> *" . . in the context of developing advanced nuclear fuel cycles and next generation technologies for nuclear energy, the United States should reexamine its policies to allow for research, development and deployment of fuel conditioning methods (such as pyroprocessing) that reduce waste streams and enhance proliferation resistance."*

The United States has, in the past, discouraged the use of some spent fuel technologies because of concerns regarding the proliferation characteristics of older technologies that could separate plutonium and therefore could support covert weapons activities. If research into proliferation-resistant fuel cycle technologies proves successful, the United States could be in a position to make available technologies that not only avoid the problems of proliferation-prone technologies, but also enhance the proliferation characteristics of current U.S. practice.

Such technologies cannot be ushered forth without substantial new investments in research and development. Further, to deploy these technologies would require government and industry to spend billions in new, commercial-scale plants. Refined estimates would require the research, development and design work outlined in this report.

II. AFCI Series One

The mission of AFCI Series One would be to develop proliferation-resistant technologies that could address the intermediate-term issues associated with the management of spent nuclear fuel, specifically by:

- reducing the cost of spent nuclear fuel disposal by reducing the volume of high-level waste from commercial nuclear power, and

- reducing the long-term proliferation threat posed by plutonium contained in spent nuclear fuel.

DOE believes that, after a focused five-year research program, these new technologies can be sufficiently developed to support the Department's need to make policy recommendations to Congress between 2007 and 2010 with regard to the technical need for a second geologic repository.

While there are treatment technologies used around the world today that can reduce the volume of high-level waste, they engender significant proliferation concerns that limit their widespread application. Therefore, new treatment technologies should be innately proliferation resistant and achieve our technical goals while avoiding the problems that have restricted the use of spent fuel treatment technologies in the past. Further, in order to enable the United States to consume the large inventory of fissile plutonium in commercial spent nuclear fuel in a proliferation-resistant manner, it will be necessary to develop advanced nuclear fuels that can be used in today's commercial nuclear power plants.

Enhancing Spent Nuclear Fuel Disposal

Enhancing the disposal of spent nuclear fuel could be accomplished through the use of advanced treatment and transmutation technologies. The complexities and challenges associated with the development of proliferation-resistant recycle technologies are formidable. Significant technical challenges arise from the requirement that all spent fuel treatment and transmutation technologies be proliferation-resistant. Recently-developed advanced surveillance technologies must be leveraged to further ensure both the proliferation-resistance of any required fuel cycle facilities and that inherent material losses are exceptionally low.

Treatment Technologies

Management of spent nuclear fuel, specifically the reduction of mass and volume of high-level nuclear waste, requires the use of treatment technologies that separate the constituents of spent nuclear fuel into (See Figure II-1):

- uranium (which is approximately 96 percent of the spent fuel);
- short-lived radioactive elements (which decay to harmless species over few hundred years); and
- long-lived radioactive materials such as plutonium, americium, and other actinides.

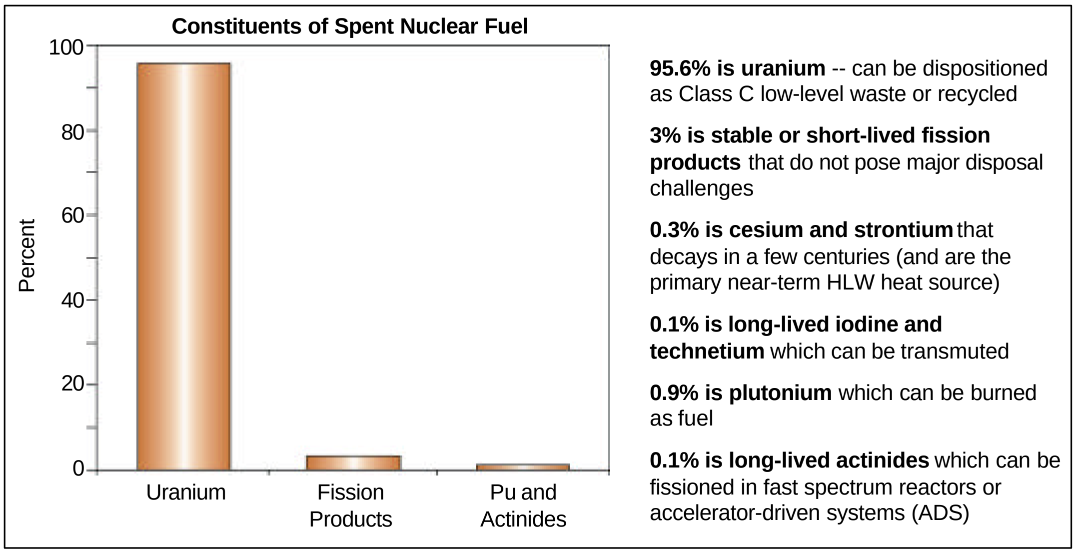


***Figure II-1:* Spent fuel is nearly 96 percent uranium—simply removing this material would result in a dramatic reduction in the volume of nuclear waste.**

Aqueous chemical treatment of various types of spent nuclear fuel has been practiced on a commercial scale in a number of countries. A treatment process known as Plutonium-URanium EXtraction (PUREX), developed by the United States in the late 1940s, is in active use on a large scale in France, Russia, and the United Kingdom.

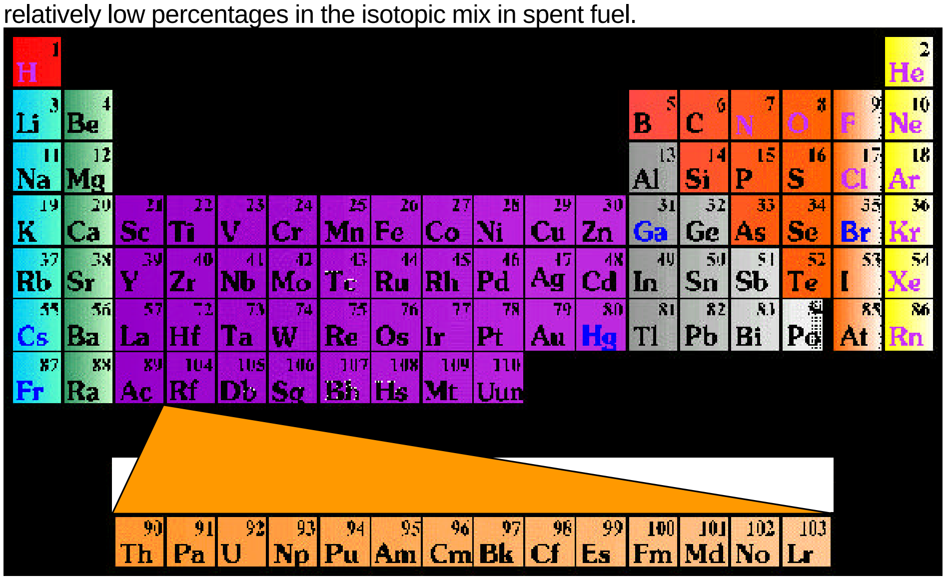
In the PUREX process, spent fuel is dissolved in acid and fed through a solvent extraction process. The process separates both uranium and plutonium. Afterward, both short and long-lived radioactive materials (neptunium, americium, *etc*.) are directed to a liquid waste stream, mixed with borosilicate glass, and poured into canisters where it vitrifies. This configuration is highly-suitable for long-term storage or disposal. Although PUREX can be used to reduce spent fuel volume by removing the uranium, it has two major drawbacks: it produces separated plutonium (a proliferation concern) and it generates a relatively large amount of high-level waste.

In the past few years, DOE has made significant advancements in treatment technology that has both important environmental and proliferation-resistant advantages over PUREX. This treatment technology, known as URanium EXtraction (UREX), can reduce the proliferation risk by avoiding the separation of plutonium from other radioactive species – thereby rendering the plutonium unusable for weapons applications.

In the UREX process, plutonium, and other transuranics, and fission products are extracted in a single stream from which transuranics could be extracted for reuse in nuclear fuel. The feature of UREX that makes it much more proliferation-resistant than PUREX is the continual presence of minor actinides, the high radioactivity and thermal characteristics of which make these materials relatively unattractive to potential proliferaters. Additionally, because UREX does not place these actinides in the waste stream, there could be a significant reduction in the amount of high-level waste produced. Short-lived radioactive isotopes are separated and may be stored and allowed to decay to harmless elements over several decades.

WHAT ARE ACTINIDES?

Actinides are a series of elements in the periodic table with atomic numbers between 89 and 104. They are heavy elements with similar chemical properties that resemble the rare earth (or lanthanide) series. Uranium (U), plutonium (Pu), neptunium (Np), americium (Am), and curium (Cm) are the actinides of importance in determining the long term toxicity and heat load of spent nuclear fuel. Actinides with atomic numbers higher than uranium are called ***transuranics***, and include Np, Pu, Am and Cm. Np, Am, and Cm are known as ***minor actinides*** because of their relatively low percentages in the isotopic mix in spent fuel.



Further, experiments completed in 2002 have proven UREX to be capable of removing uranium from waste at such a high level of purity that we expect it to be sufficiently free of high-level radioactive contaminants to allow it to be disposed of as low-level waste or reused as reactor fuel. These laboratory-scale UREX tests have proven uranium separation at purity levels of 99.999 percent. If spent fuel were processed in this manner, the potential exists to reduce significantly the volume of high-level waste. An additional advantage of UREX is the use of acetohydroxamic acid, which enables the use of chemical processes that are far more environmentally-friendly than PUREX.

AFCI Series One research would include the continued development of aqueous chemical treatment technologies including the possible demonstration of UREX at a scale relevant to its eventual commercial use.

An advanced development of UREX, referred to as "UREX+," would be a key element of an AFCI program. This additional research would evaluate different aqueous chemical treatment methods to separate selected actinide and fission product isotopes from the UREX stream after the uranium has been extracted in a manner that minimizes waste. For example, UREX+ would provide mixtures of plutonium and selected minor actinides for preparing proliferation-resistant fuels. Long-lived fission products, iodine-129 and technitium-99, which are major contributors to the long-term radiotoxicity from spent fuel, could be separated for incorporation into targets for destruction in reactors. This work would allow the program to obtain a detailed understanding of all waste streams, the data needed for understanding what would be needed in a commercial scale treatment facility, and provide the basis for estimating the cost to design, build, and operate such a facility.

If implemented successfully, this treatment technology could significantly reduce the volume of high-level waste from commercial nuclear power (see Figure II-2). This accomplishment would reduce the cost of the first repository and potentially eliminate the technical requirement for a second.

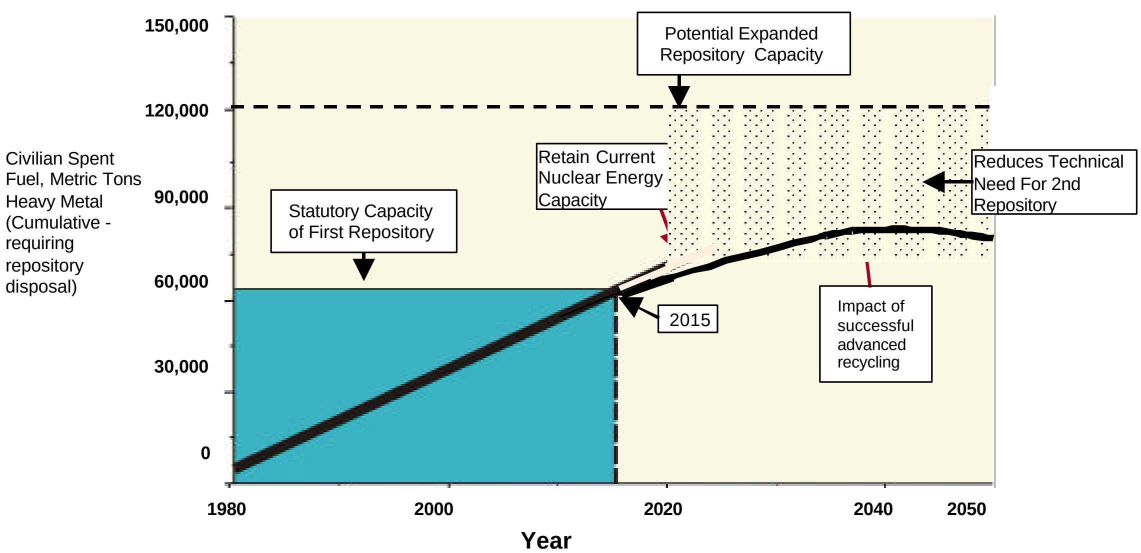


Figure II-2: **As an example, if AFCI technologies were commercialized in time to impact the first repository, they could provide the volume reduction required to avoid a second such facility**

Key programmatic treatment technology elements for AFCI Series One would include: 1) laboratory demonstration of UREX+ using radioactive materials; 2) engineering scale demonstration of UREX+; 3) laboratory demonstration of PYROX (pyrochemical dry treatment) technology using spent LWR fuel; 4) demonstration of PYROX actinide recovery, 5) engineering scale demonstration of PYROX using radioactive materials, 6) demonstration of large-scale metal waste form technology; and 7) treatment facility requirements, costs, and design studies.

Fuel Technologies

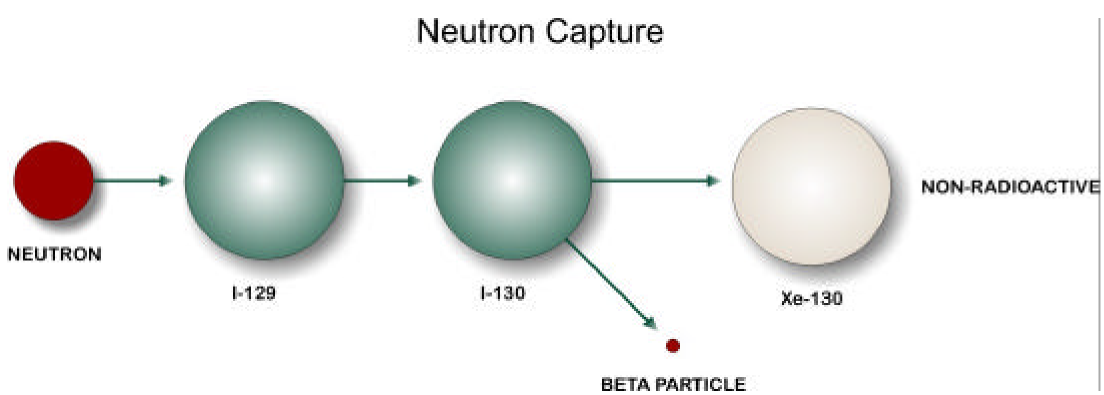
The UREX treatment technology, combined with additional processing steps, provides the ability to produce proliferation-resistant transmutation fuels for use in LWRs or gas-cooled reactors. Successful implementation of this technology would require dealing with several issues such as fabrication and testing of transplutonic-bearing fuels, which would require remote fabrication.

To support this effort, research on transmutation fuels would focus on the development of proliferation-resistant fuel forms, preliminary fuel irradiation testing, and analysis of the resulting transmutation system (including waste streams). In the case of LWR transmutation fuels, several technology options would be considered, including the French CORAIL, Advanced Plutonium Assembly systems, advanced assembly designs, and inert matrix/non-fertile fuel concepts.

Gas-cooled reactors use very small spherical fuel particles, which if manufactured with advanced coating technology, are strong enough to permit much higher burnups than are possible with LWRs, and are difficult to reprocess. Very high destruction levels of plutonium (over 90 percent) have already been demonstrated using pure plutonium fuels; however, the challenge remains to achieve these impressive burnups with proliferation-resistant fuels. Research is needed to address this challenge and will include the development of proliferation-resistant fuel forms, fuel irradiation testing at the High Flux Isotope Reactor at Oak Ridge National Laboratory or the Advanced Test Reactor (ATR) at the Idaho National Engineering and Environmental Laboratory (INEEL), and analysis of the resulting transmutation system performance for gas-cooled reactor fuel.

WHAT IS TRANSMUTATION?

Transmutation refers to the ability to transform one atom into another by changing its nuclear structure. This is accomplished by bombarding the atoms of interest with neutrons either in an accelerator or a nuclear reactor. In the context of spent nuclear fuel, transmutation can convert plutonium and other actinides into isotopes with more favorable characteristics.



Reducing the Proliferation Threat from Plutonium in Spent Nuclear Fuels

There are significant proliferation concerns associated with the plutonium present in spent nuclear fuel. While it is initially difficult to covertly extract plutonium from spent fuel due to the intense radioactivity of the fission products found in spent fuel, this risk drops significantly over time. The dominant fission products producing the radiation field surrounding spent nuclear fuel are strontium-90 and cesium-137. Both species have 30-year half-lives, and as a result, the protection provided by fission product radiation is halved every 30 years. Since repositories are designed to provide safe containment for tens of thousands of years, diversion protection from the radiation field gradually becomes lower with time. As a result, the radiation levels become low enough over 50 to 100 years that the materials could be removed with manageable exposure to a potential proliferant.

Current plans call for the repository to provide diversion protection through a series of costly security measures in addition to the radiation field. Transmutation provides another approach to proliferation protection that has many desirable features. Destroying plutonium using transmutation technology will significantly reduce the physical protection and material control and accounting requirements, resulting in potential cost savings in addition to reducing the proliferation risk from these materials.

Energy Benefits

In addition to the volume reduction and proliferation-resistance benefits described above, AFCI Series One could also recover from spent nuclear fuel certain materials, including plutonium, that could be re-used as fuel to generate additional electricity. Plutonium inventory builds up as spent fuel accumulates. Today, approximately 440 MT of plutonium are contained in spent fuel stored at various nuclear power plant sites in the United States. If this plutonium were treated and recycled into existing power plants, there would be sufficient fuel to operate all currently operating U.S. commercial nuclear plants – a fifth of the Nation's electric generation capacity – for approximately 4.5 years.

Principal Science and Technology Challenges

Successful implementation of AFCI Series One technologies would require the resolution of several scientific and engineering challenges. The most difficult challenges are associated with the development and design of the UREX+ processing plant and the associated fuel fabrication facility. While both of these facilities could be designed to be environmentally-friendly and proliferation-resistant, the real challenges come in the area of accomplishing these features economically, while maintaining exceptionally-low material losses. Material losses are key because they affect the radiological impact of plutonium and higher actinides. To achieve programmatic goals of reducing plutonium and minor actinides in the final waste stream to approximately 0.2 percent will be a major challenge.

The second major challenge of Series One is the development and licensing of fuel (by the U.S. Nuclear Regulatory Commission) to recycle plutonium and neptunium in existing or advanced light water reactors, which commercial U.S. nuclear utilities will purchase and use. Current research supports incorporating features that make this new fuel proliferation-resistant, however this aspect of the fuel also makes it more expensive to handle. Preliminary discussions with one commercial fuel supplier supports a view that this new fuel would be acceptable if the price is sufficiently less than normal commercial enriched uranium fuel to off-set costs associated with the handling of proliferation-resistant fuel.

AFCI Series One fuel development, testing, and licensing activities would be designed to lead to recycle of a proliferation-resistant plutonium and neptunium fuel for use in commercial nuclear power plants. The key areas of research include; 1) determining fuel design and specifications, 2) developing fuel fabrication technologies, and 3) performing irradiation testing of sample fuel forms in the ATR at INEEL. This work would include planning and preparations for testing a Lead-Test-Assembly (LTA) in a commercial nuclear power plant and development of fuel fabrication facility conceptual design, requirements, and costs.

Summary/Conclusions

The goal of the AFCI Series One technology effort is to develop advanced proliferation-resistant fuel treatment technologies and the basis for transmutation fuel technologies that could be deployed in a time frame relevant to the development of the Nation's first high-level waste repository. The research and development proposed for AFCI Series One would provide the information necessary to determine whether or not to proceed to the next phase of the program that would include industrial-scale demonstrations of the processes.

Significant advancements have been made at the laboratory scale for proliferation-resistant treatment technologies (UREX). This technology would require additional research and development to provide specific feed material from UREX+ to manufacture proliferation-resistant transmutation fuels for both LWRs and gas-cooled reactors. The real challenge is, therefore, the development of proliferation-resistant fuels, the fabrication of those fuels, and development of a sound basis upon which to estimate the costs associated with implementing these technologies.

It should also be noted that transmutation of plutonium and other actinides contained in spent nuclear fuel in nuclear power plants could provide a 25 percent increase in the energy extracted from nuclear fuel compared to using current reactor systems with a once-through cycle. A more important contribution may come from the proliferation perspective, specifically, the elimination of much of the plutonium present in spent nuclear fuel that transmutation could make possible.

The development of the Nation's first repository is quite important to the future of nuclear energy in the United States, but it has been a long and difficult process. Based on that experience, contemplating a time when a second—and perhaps more—deep geologic repository may be needed, is not a comforting prospect for those who anticipate an expanded role for nuclear energy in the future. Spent fuel treatment and transmutation can expand the technical capacity of the first repository and reduce the scientific need for a second. This technology, therefore, can help ensure that nuclear energy will be able to contribute to the Nation's energy supply far into the future.

III. AFCI Series Two

AFCI Series Two would focus on the development of proliferation-resistant technologies that would address the long-term issues associated with management of spent nuclear fuel, specifically, a significant reduction in the long-term radiotoxicity and heat load of high-level nuclear waste. Successful deployment of AFCI Series Two technologies could:

- reduce the cost of spent fuel disposal by reducing the long-term radiotoxicity and heat load, and

- support the development of advanced, next-generation nuclear fuel cycles that support an economic, proliferation-resistant long-term future for nuclear power.

Technology development would focus on next-generation spent nuclear fuel treatment and transmutation fuel technologies. DOE believes that sufficient information could become available from AFCI Series Two research and development to evaluate whether to proceed with the full demonstration of these technologies. Another significant research, development and design challenge necessary to support an informed decision would be the development of preliminary design and deployment cost estimates for required facilities and program schedules and estimation of the projected costs and benefits associated with the deployment of these technologies.

What is Radiotoxicity?

Radiotoxicity refers to the direct adverse biological effect on humans of materials in spent nuclear fuel. The materials of long-lived toxic concern in spent fuel include plutonium; minor actinides such as neptunium, americium, and curium; and other long-term toxic materials such as the radioactive fission products (*e.g.*, iodine and technetium)

In general, AFCI Series Two would focus on the fuel cycle technology associated with fast spectrum systems (which may exist in tandem with the light water or gas-cooled thermal reactors discussed in Section II of this report) and associated proliferation-resistant treatment technologies to establish an economic, closed fuel cycle. Fast reactor technology is of considerable interest to the program because, unlike light water or gas reactor technologies in use today or contemplated for near-term deployment, fast reactor systems produce very high energy neutrons that can transmute a wide array of toxic radioactive species (particularly actinides such as americium, which are generated in today's reactors). These toxic radioactive materials would otherwise exist for hundreds of thousands of years in geologic repositories.

Successful deployment of AFCI Series Two technologies could provide both energy and economic benefits to the United States. Next-generation nuclear fuel technologies used in combination with advanced energy systems could extract significant additional energy from the materials in commercial nuclear power plant spent fuel while at the same time dramatically reducing both the radiotoxicity and repository heat loading. These reductions could reduce repository costs significantly.

As illustrated in Figure III-1, the radiotoxicity of spent fuel declines as a function of time. Even though natural decay significantly reduces spent fuel toxicity in the very long term, a major reduction could be effected more quickly if advanced treatment and transmutation were successful in reducing the quantity of toxic material. Current commercial spent fuel placed in a repository would take about 300,000 years to decay to the same level of toxicity as natural uranium ore. Scientific investigation has demonstrated that the first repository can be sited in a manner that would isolate nuclear materials from the environment over this period.

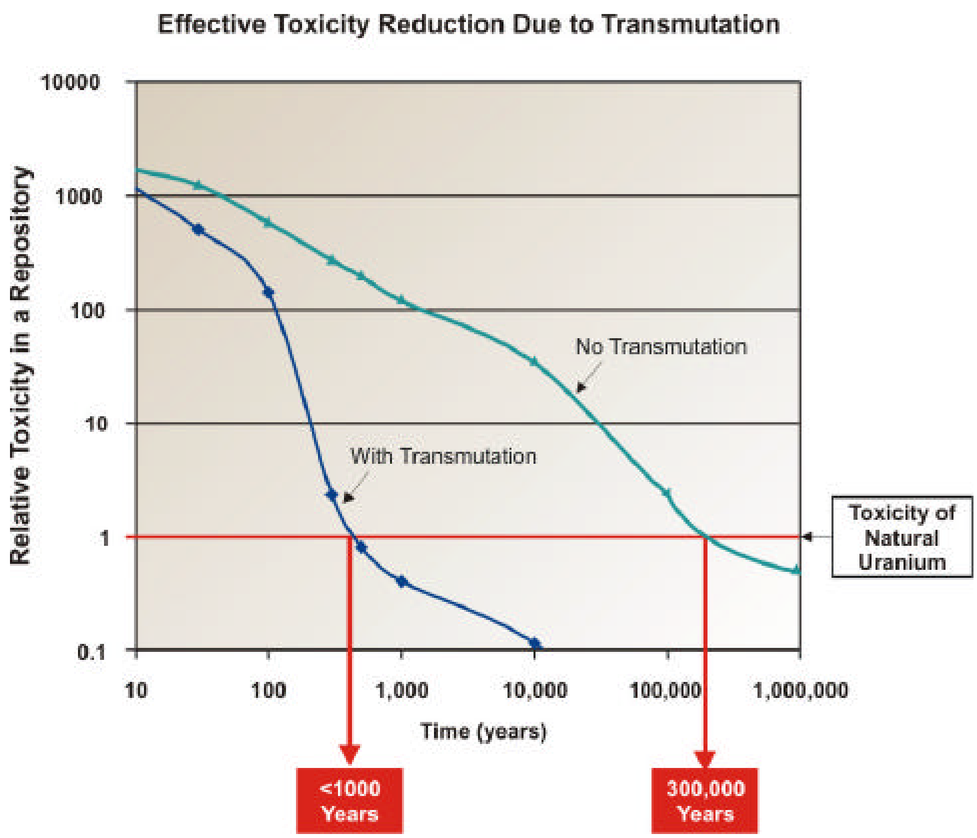


Figure III-1***:*** **Advanced spent fuel treatment and transmutation can lead to large reductions in the long-term radiotoxicity of materials contained in a geologic repository**

Nevertheless, the successful application of advanced treatment and transmutation fuel technologies in fast spectrum reactors may result in the reduction of the toxicity of high-level waste from spent fuel placed in the repository to the same level as that of natural uranium ore in 1,000 years or less. This is an aggressive technology goal and achieving it would require the successful development of advanced transmutation fuels and associated treatment technologies (such as UREX) that would enable the use of fast neutron systems to destroy long-lived radioactive species.

Because of the potential to use spent fuel processing and transmutation to benefit the management of radioactive waste, there is significant international interest in the AFCI Series Two research and development program. For example, France has a transmutation research program in place that began in 1991[1], and the European Union has implemented transmutation research in their Fifth Framework research program[2]. Work done by other countries is already helping DOE accelerate its research and reduce program costs. In the past two years, DOE has established international agreements with France and Switzerland on joint collaboration into transmutation technologies. To date, these agreements have provided the United States with necessary and extensive research and experimental data that would have cost over $100 million for DOE to develop on its own. DOE is also in the process of exploring opportunities for international cooperation in this topic area with other countries pursuing advanced fuel cycles.

Research Effort Required to Develop Next-Generation Nuclear Fuel Technologies

The research and development effort that would be required to accomplish the goals of AFCI Series Two can be best considered as a three-phase program with decision points at the end of each phase. The phases are as follows:

- Phase I *Basic Technology Evaluation (conducted during FY 2000 through FY 2002)*
- Phase II *Proof-of-Principle*
- Phase III *Proof-of-Performance*

Phase I, the initial evaluation of technologies, was completed at the end of fiscal year 2002. During Phase I, technologies and systems have been identified that have the potential to meet the program goals to reduce waste volume, toxicity, heat generation, and proliferation risks when compared to current practices and plans. The Phase I effort has benefited from initial research and development activities conducted under the AAA Program over the last few years and from research activities conducted overseas by collaborating nations. The most promising technologies will be identified for focused research in Phase II. During Phase II, laboratory and larger scaled testing and analysis will be conducted to clarify the options and provide the information necessary to choose a path forward for Phase III, a proof-of-performance demonstration.

<u>Phase I - Basic Technology Evaluation</u>

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1 France's program was established and required by *Loi n^o 91-381 du 30 decembre 1991 relative aux recerches sur la gestion des dechets radioactifs* and its subsequent amendments.

2 *Council decision of 22 December 1998 concerning the Fifth framework Programme of the European Atomic Energy Community (Euratom) for research and training activities (1998 to 2002) (1999/64/Euratom),* Annex II.II.(a).2.(ii).

During this phase, the basic technologies necessary to initiate activities to attain the AFCI Series Two goals were developed and evaluated. At the end of this phase, candidate systems for spent fuel treatment and transmutation that the AAA Program considered were reduced to the most promising systems for long-term development. The primary candidate systems involve fast spectrum reactors[3], possibly augmented with limited accelerator-driven fast spectrum subcritical systems[4]. Phase I system studies have shown that stand-alone accelerator-driven systems (ADS) are not an economically acceptable solution to deal with spent fuel[5]. Complexes of large ADSs would be very expensive to build and operate and would be unlikely prospects for commercial deployment. Phase I evaluations, conducted under the oversight of NERAC's Advanced Nuclear Transformation Technology Subcommittee, indicated that combined systems using commercial light water, gas-cooled, and advanced fast spectrum reactors appear to provide the most feasible and cost-effective approach to transmutation[6]. Application of relatively small, central ADSs could augment this approach by providing a "final burn" to assure the lowest possible level of long-lived radioactive elements in the final waste form.

For any of these options to prove viable, they must be economically competitive with other methods of producing electricity as well as being extraordinarily safe, reliable, and proliferation resistant. Development of advanced fast spectrum reactor systems that meet these requirements is beyond the scope of AFCI; however, such technologies are included in the Generation IV Nuclear Energy Systems effort currently being pursued by the United States and nine partner countries. Where Generation IV is DOE's initiative to develop next-generation *reactors* that can be commercially-deployed, the AFCI is the complementary DOE program that will research and develop the advanced treatment technologies to prepare and process transmutation *fuels* for fast systems identified by the Generation IV activity.

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3 Fast Spectrum Reactors (also known as fast reactors) are nuclear reactors that use the special properties of neutrons at high energy to maximize the energy withdrawn from a specific amount of uranium fuel while minimizing the total waste discharged. When a uranium atom fissions (or separates into smaller atoms) in a nuclear reactor and releases energy, neutrons are released at high energy. Fast spectrum reactors avoid using light materials, like water or hydrogen, which would slow neutrons down.

4 A sub-critical system, such as a fast spectrum accelerator, supplies the neutrons that are necessary to maintain the reaction. A critical system, such as a fast spectrum reactor, would be self-sustaining.

5 Van Tuyle, Gregory J. et at.; Candidate Approaches for an Integrated Waste Management Strategy – Scoping Evaluation; September 2001.

6 Richter, Burton, et al.; *Report of the Advanced Nuclear Transformation Technology Subcommittee of the Technology Subcommittee of the Technology Subcommittee of the Nuclear Energy Research Advisory Committee*; 15 April 2002; pp. 3-4.

Major accomplishments during Phase I included the following:

- treatment of spent fuel to demonstrate the feasibility of obtaining high purity uranium from spent fuel,

- successful manufacture of transmutation fuels (*e.g.*, metal and nitride) containing various combinations of plutonium and minor actinides in preparation for irradiation testing in fiscal year 2003,

- building and starting operation of a lead-bismuth materials test loop at Los Alamos to investigate materials behavior in high-temperature liquid metal environments, and

- completion of studies that analyzed several transmutation systems to determine which have the highest potential to significantly reduce radiotoxicity.

<u>Phase II - Proof-of-Principle</u>

Research conducted under Phase II of AFCI Series Two would be designed to determine the capability of introducing advanced transmutation systems in a cost-effective, environmentally responsible, and proliferation-resistant manner. Systems identified as the most promising during Phase I would be at the center of these investigations, and the research would determine which of these technologies could be relied upon to reduce the cost of spent fuel disposal and how significant a factor it should be in the decision regarding a second repository. (It must again be stressed, as explained in Section I (page I-8), that none of the AFCI activities discussed in this section or elsewhere in the report will have any impact on the need for the first repository.) This work would evaluate whether a full-scale demonstration of these technologies as part of a Proof-of-Performance phase (Phase III) warrants consideration. The technology areas that would be pursued in Phase II include the following:

- development and demonstration of advanced proliferation-resistant treatment technologies,

- development and testing of advanced transmutation fuels, and

- physics experiments and materials research related to accelerator-driven systems.

Development and Demonstration of Advanced Proliferation-Resistant Treatment Technologies

AFCI Series One research on advanced proliferation-resistant treatment technologies would focus on conducting a demonstration of the UREX process to separate uranium from LWR spent nuclear fuel at a very high level of purity. Recent successful demonstration that UREX separations can achieve the required level of purity means that the UREX process developed for AFCI Series One is likely also to provide the front-end of the spent fuel treatment system needed to process transmutation fuels for AFCI Series Two. AFCI Series Two would develop advanced technologies to treat actinides for processing into proliferation-resistant fuel for fast spectrum systems.

Pyroprocessing technology[7], which is currently under development at Argonne National Laboratory, would be prominent among the technology approaches considered to prepare fuel for transmutation systems. The program would also investigate a new area of pyroprocessing research called "oxide reduction," which would prepare spent fuel from LWRs for introduction into a pyroprocess. This new technology has the potential to replace the UREX process in AFCI Series Two. If successful, this new technology would represent an advance in efficiency and proliferation resistance over chemical methods for Series Two systems. A key item of interest in pyroprocessing treatment deals with the efficiency of the process in terms of determining whether the losses of material from the pyroprocess are sufficiently small and whether the resultant waste forms are acceptable to the repository. This work would be completed in Phase II and would be an alternative for consideration in selecting a system concept to be pursued in Phase III.

In addition to pyroprocessing techniques, AFCI Series Two could engage the international community in a full exploration of other advanced treatment options. One area that could be explored includes techniques known as "fluoride volatility" processes that involve the fluorination of spent fuel with fluorine gas and the subsequent separation of resultant volatile compounds (*e.g.,* UF_6) from non-volatile (*e.g.,* PuF_4) compounds of fluorine. This technology has considerable promise as a proliferation-resistant means of treating spent fuel while minimizing the generation of nuclear wastes. Another interesting advanced technology concept is being pursued at the Russian Research Center "Kurchatov Institute" and applies a plasma process to treat spent fuel. Which of the various advanced approaches to fuel treatment would be selected for long-term development remains a subject of further exploration.

AFCI is designed with the recognition that both "dry" processes (like pyroprocessing) and aqueous processes (like UREX+) may be needed to serve complementary roles in an advanced treatment system. While these technologies are not necessarily competitive options in AFCI Series Two, they do have very different characteristics. Pyroprocessing, for example, operates at high temperatures compared to aqueous processes, and is not designed to remove pure plutonium during the treatment of spent fuel – which makes the fuel derived from the spent fuel too radioactive to facilitate its use in weapons. However, it has never been proven to operate at commercial scales, though experiments and work performed by DOE over the last several years point to the technical issues that would need to be resolved to support larger-scale activities.

As an aqueous process, UREX+ can be assumed to be similar in some respects to commercial technologies in use in Europe. Experts consulted for this report believe that UREX+ plants could be built to handle commercial scale spent fuel treatment (*e.g.*, 1,500 to 2,000 metric tonnes per year). On the other hand, pyroprocessing is better suited for dealing with large concentrations of transuranics, and hence best suited for fast spectrum reactor systems. Pyroprocessing also facilitates the fabrication of metal fuels, which may prove essential in fast reactor systems.
The following accomplishments are anticipated during Phase II in the advanced proliferation-resistant treatment technologies area:

7 Pyroprocessing (also known as electrometallurgical treatment) is a process used to separate fuel elements discharged from a nuclear reactor into two separate sets of material: fuel material that can be recycled back into the reactor and waste material that is disposed. The pyroprocess places fuel elements in a liquid salt bath and uses electrical current to draw the different components of the fuel element towards separate collection areas.

- investigation and selection of an advanced separations technology for long-term application,

- development and hot demonstration of an electrochemical oxide reduction and electrorefining process to enable separation of actinides from fission products, and

- hot demonstration of a process to prepare actinides from LWR spent fuel for transmutation.

Development and Testing of Advanced Transmutation Fuels

While plutonium-based fuels have been manufactured on a commercial basis, almost no work has been done on making or irradiating fuels that contain neptunium, americium, or curium. Transmutation fuels that can significantly destroy the higher actinides should be capable of very high burnups to minimize the number of recycles in order to reduce material losses due to separations and refabrication processes. They would also need to be easily fabricated in hot cells or some other remote environment due to the high radiation levels from the minor actinides. If these advanced fuels are to be useful candidates for potential deployment with Generation IV type systems, research, development, and testing would be needed beyond Phase II. AFCI Series Two would apply considerable effort to evaluating the various fuel types that could serve as an optimum fuel for fast spectrum reactor or accelerator-driven transmutation systems.

The determination of the optimum fuel form for transmutation – a fuel that may be easily fabricated using remote handling technologies, contributes to the safe operation of the reactor, and results in a final waste form acceptable for Yucca Mountain – is a major research objective of the program. Oxide, nitride, metallic, dispersion, ceramic, and coated particle fuel forms are currently under investigation. Fabrication of several test fuel specimens of these fuel forms containing plutonium mixed with minor actinides is underway. The Department plans to irradiate these fuels in the ATR in Idaho in fiscal year 2003, with a more ambitious follow-on irradiation program to be carried out in France by other European partners. A consortium of institutions is planning the construction of an experimental assembly containing minor actinide fuels that would come from several countries; this assembly would be irradiated in a French fast spectrum reactor (PHENIX). Successful testing in the ATR and initiation of the French PHENIX tests during Phase II would permit DOE to select the most promising path forward for AFCI Series Two transmutation fuels including planning for potential Phase III scaled-up fast spectrum irradiations in foreign facilities.

Fast spectrum systems can be either fast reactors (which employ critical reactor cores that operate 12-to-18 months between refueling cycles) or accelerator-driven systems that employ reactor cores that are sub-critical by nature (*i.e.,* they need a constant source of neutrons to maintain a normal operating state). The external source of neutrons is produced by an accelerator and a target system. Both systems employ fast neutrons; however the accelerator system has the advantage that it can totally transmute all radioactive elements without producing any plutonium in the process. Accelerator systems are more expensive than fast reactors, and require significantly more research and development, although the fuel technology is basically the same.

While the Department, based on the systems analysis carried out in Phase I of this research endeavor, does not expect accelerator transmutation systems to be used as the primary transmuters of the long-lived toxic materials present in spent fuel, they may have an important role in assuring the very low levels of toxicity that serve as the technology goals of this activity[8]. The relatively high construction and operating costs of accelerator-based systems make them unsatisfactory for wide-spread application as commercial-scale transmuters. Fast reactor systems, however, may prove sufficiently economic to justify their eventual deployment—this is a key element of evaluation in the multinational Generation IV Nuclear Energy Systems Initiative. (The *Generation IV International Forum: Update, October 2002* is included as Appendix B.)

The following accomplishments would be anticipated during Phase II in the advanced transmutation fuels technology area:

- screening irradiation tests of several fuel forms in the ATR and post-irradiation examination and analysis to help select fuels for the follow-on proof-of-performance Phase III;

- fabrication and initiation of screening irradiation tests of several fuel forms in the French PHENIX fast test reactor;

- fabrication and initiation of irradiation testing of gas-cooled reactor TRISO particle transmutation fuel for use in a fast neutron spectrum;

- development of process flow sheets and relative capital and production costs for fabrication of the several candidate fuel types;

- measurement and characterization of the physical, chemical, and thermal properties of transmutation fuel types and their incorporation into a *Fuels Handbook*; and

- development and validation of predictive fuel performance and properties using ATR test fuel irradiation data.

Accelerator Driven Systems Physics and Materials Research and Development

Many countries are considering ADSs as a viable approach to transmutation because these systems may be capable of destroying long-lived radioactive isotopes of all types without making plutonium. An accelerator driven system consists of an accelerator that produces high energy protons that strike a heavy metal target to produce high energy (fast) neutrons through a spallation process to drive a subcritical reactor assembly. This research includes understanding the physics of coupled accelerator-driven fast spectrum systems and the related spallation target and materials issues. The United States has been able to acquire valuable experimental data from French researchers and from projects funded by the European Commission that would reduce the cost of this program. In addition, UNLV has been conducting research in several areas related to accelerator driven systems. Of primary importance, to the program, UNLV has been conducting basic research in the area of lead-bismuth corrosion technology. This research not only supports accelerator driven systems, but also supports development of Generation IV energy systems.

8 Richter, et al. *Op. Cit.*

A critical Phase II physics experiment would couple an accelerator with a subcritical multiplier test facility in Europe or possibly in this country in the TREAT facility in Idaho. This activity would provide crucial physics information required to design and safely operate accelerator driven systems.

Spallation target materials are also being developed for use as a coupling device between an accelerator and a fast spectrum reactor. In Phase II, a decision would need to be made on whether lead-bismuth is acceptable for the target material or a sodium cooled-tungsten target configuration is needed. The program has built and initiated operation of a lead-bismuth Materials Test Loop that is currently providing important data needed to operate large spallation targets. In collaboration with Swiss, French, German, and Italian organizations, DOE is participating in the construction of a powerful spallation target that is planned to be operating by 2005 and that would provide experimental data needed for the Phase II materials decisions. High temperature behavior of materials in a fast spectrum system would also be evaluated in Phase II. Regardless of the path forward chosen after Phase II, the information derived in this work area should facilitate more efficient and economic designs in Phase III. The following accomplishments are anticipated during Phase II in the ADS Physics and Materials Research and Development area:

- completion of tests on the safe operation and controllability of a coupled accelerator driven subcritical multiplier system;

- completion of materials corrosion, thermo-hydraulics, thermodynamic, and irradiation

- tests of lead bismuth-cooled systems needed to select reference target and multiplier configuration to be used in the proof-of-performance demonstration phase; and

- completion of integral spallation target testing at the MEGAPIE facility in Switzerland.

<u>Phase III - Proof-of-Performance</u>

A decision to proceed to Phase III, a full-scale Proof-of-Performance demonstration, would be based on information developed in Phase II. Conclusions made in Phase II that would support moving forward with Phase III include final selection and development of an advanced treatment process, selection and demonstration of optimum fuel forms, selection of an ideal ADS target material, and a comprehensive assessment of the costs and benefits of each of the alternatives to complete a proof-of-performance and to proceed with implementation. The goal of Phase III would be to complete confirmatory testing of selected spent fuel treatment and transmutation fuel technologies and to resolve design and engineering issues through full-scale demonstrations. A series of tests, including irradiation and recycling, would be performed to demonstrate fast spectrum irradiation and fuel cycle processing capabilities and provide a firm basis for estimating the economic and environmental impacts of these technologies. New, scalable fuel fabrication, treatment, and fast spectrum test facilities in the United States or in partner countries would likely be needed to complete this work.

At the end of this phase, all major technical, design, economic, and engineering issues associated with the fuel cycles investigated in Phases II and III would be resolved. Additionally, data would be available to define an architecture for commercial deployment with considerable confidence regarding system costs and performance. The Phase III technology development goal, if accomplished on a timely basis, would provide confirmation of the advanced fuel cycle designs required for successful implementation of Generation IV systems.

Because it is likely that new facilities would be required to demonstrate the commercial viability of AFCI technologies, while also resolving key engineering and operations issues, the program would continue its strong international cooperative program during Phase III. Even at this early stage of the program's development, France has expressed interest in such cooperative efforts.

International research, development and design collaborations would be essential because of the complexity and challenges associated with proliferation-resistant recycling technologies. Particularly important would be the goal of achieving material losses low enough to assure that the relative toxicity of the resulting waste (destined for the repository) could decay to a toxicity level equivalent to that of natural uranium within 1,000 years. Furthermore, international partners such as France have extensive experience in recycle technologies. The AFCI program would seek to combine the experience of these partners with the program's own new challenging research, development and design to achieve cost-effective and environmentally-friendly construction and operation of AFCI facilities.

Principal Science and Technology Challenges

Successful implementation of Series Two technologies would also require resolution of several scientific and engineering challenges. In Series Two, the most difficult challenges are associated with developing and designing commercial-scale advanced fuel treatment processes that are economic and proliferation-resistant--that is, exceptionally low materials losses. Current research supports the ability to incorporate proliferation-resistance, however to do so economically is the challenge. Research and demonstration of a scaled facility would be required to understand fully the commercial feasibility of this technology.

The second major challenge of Series Two would be the development and licensing of Generation IV transmutation fuel and the associated materials issue. While the metal fuel form is well understood, the more advanced fuels, such as nitride fuels, provide the promise of exceptionally high burn-up, which improves the transmutation rate. Achieving this benefit, however, requires major advancements in fuel cladding materials issues.

The third major challenge of Series Two would be the development of coupled spallation-target/sub-critical reactor cores, and their associated systems. Achievement of this requirement would depend on the selection of accelerator-driven systems for the final burn. If systems studies support this technology, then this challenge must be met.

Transmutation Technology Development

Research and development for AFCI Series Two transmutation technology development would cover three major areas: 1) transmutation physics, 2) transmutation materials, and 3) accelerator driven systems. Transmutation physics focuses on research to provide critical nuclear cross-section data in the thermal, epithermal, and fast neutron spectra. This data is needed to ensure that transmutation rates and criticality uncertainties are understood. Analysis codes will be validated against experimental data. Transmutation materials activities will focus on; 1) analysis of the degradation of structural materials in fast neutron spectrum and accelerator generated protons and neutrons, and 2) coolant technology for critical and non-critical reactor systems. Material damage limits will be established to determine the extent to which these systems can operate before requiring replacement. Transmutation using accelerator driven systems would focus primarily on international collaboration, such as the “MEGAPIE” lead-bismuth spallation target experiment at the Paul Scherrer Institute, and the European “TRADE” experiment in Italy. These collaborations will level European research investments at a fraction of the cost of conducting the experiment.

Summary/Conclusions

AFCI Series Two would consist of a phased approach to developing the technologies needed to address the long-term issues associated with spent nuclear fuel management --- namely, reducing the long-term radiotoxicity and heat load. It is clear that fast neutron spectrum systems would be required to adequately destroy the long-lived toxic actinides and fission products of concern in spent fuel. During the AFCI Series Two research and development effort, advanced treatment technology and fast spectrum transmutation systems (reactors or accelerators) would be developed to achieve this goal while at the same time supporting the development of advanced, next-generation nuclear fuel cycles that can support an economic, proliferation-resistant long-term future for nuclear power.

Should AFCI Series Two proceed to Phase III (“Proof-of-Performance”), the research would provide a practical demonstration of transmutation technologies and develop the detailed information needed for their commercial deployment including their specific capabilities, operational methods, waste characteristics, and estimated volumes, costs, designs, hardware, software, and facility requirements. Successful deployment of these technologies could provide the Nation with the capability to destroy the long-lived toxic materials in spent fuel through the use of fast spectrum systems that offer the potential for new nuclear energy systems that minimize waste and eliminate or significantly reduce the technical need for a second geologic repository.

Report to Congress

on

Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research

Appendix A

107TH CONGRESS
1st Session

HOUSE OF REPRESENTATIVES

REPORT
107–258

MAKING APPROPRIATIONS FOR ENERGY AND WATER DEVELOPMENT FOR THE FISCAL YEAR ENDING SEPTEMBER 30, 2002, AND FOR OTHER PURPOSES

OCTOBER 30, 2001.—Ordered to be printed

Mr. CALLAHAN, from the committee of conference, submitted the following

CONFERENCE REPORT

[To accompany H.R. 2311]

The committee of conference on the disagreeing votes of the two Houses on the amendment of the Senate to the bill (H.R. 2311) "making appropriations for energy and water development for the fiscal year ending September 30, 2002, and for other purposes", having met, after full and free conference, have agreed to recommend and do recommend to their respective Houses as follows:

That the House recede from its disagreement to the amendment of the Senate, and agree to the same with an amendment, as follows:

In lieu of the matter stricken and inserted by said amendment, insert:

That the following sums are appropriated, out of any money in the Treasury not otherwise appropriated, for the fiscal year ending September 30, 2002, for energy and water development, and for other purposes, namely:

TITLE I

DEPARTMENT OF DEFENSE—CIVIL

DEPARTMENT OF THE ARMY

CORPS OF ENGINEERS—CIVIL

The following appropriations shall be expended under the direction of the Secretary of the Army and the supervision of the Chief of Engineers for authorized civil functions of the Department of the Army pertaining to rivers and harbors, flood control, beach erosion, and related purposes.

75–839

the AMWTP does not include financing and termination liability costs for fiscal year 2002 that would be required of the Department of Energy in the unlikely event of a termination for convenience as stipulated in the project contract.

OTHER DEFENSE ACTIVITIES

The conference agreement provides $544,044,000 for Other Defense Activities instead of $487,464,000 as proposed by the House and $564,168,000 as proposed by the Senate. Details of the conference agreement are provided below.

SECURITY AND EMERGENCY OPERATIONS

For security and emergency operations funding managed at Headquarters, the conference agreement provides $250,427,000, a reduction of $18,823,000 from the budget request. The conference agreement provides total safeguards and security funding of $1,004,716,000 which includes $754,289,000 for safeguards and security activities at Departmental field offices and facilities. For field sites, this is an increase of $63,451,000 over fiscal year 2001 funding of $665,178,000 for safeguards and security activities.

Funding of $116,500,000 is provided for nuclear safeguards and security, including $2,500,000 to procure safety locks to meet Federal specifications.

The conference agreement provides $44,927,000 for security investigations, the same as the budget request.

Funding of $10,000,000 is provided for the Corporate Management Information System in this account, a reduction of $10,000,000 from the budget request, and $5,000,000 is provided in the Departmental Administration account.

Program direction.—The conference agreement provides $79,000,000 for program direction, a decrease of $4,135,000 from the budget request.

INTELLIGENCE

The conference agreement includes $40,844,000, the same as the budget request, for the Department's intelligence program.

COUNTERINTELLIGENCE

The conference agreement includes $46,000,000, a reduction of $389,000 from the budget request, for the Department's counterintelligence program.

ADVANCED ACCELERATOR APPLICATIONS

The conference agreement provides $50,000,000 to continue research on advanced accelerator applications, including $4,500,000 for research and development of technologies for economic and environmentally-sound refinement of spent nuclear fuel at the University of Nevada-Las Vegas; $4,000,000 for reactor-based transmutation studies; and $1,500,000 for the Idaho Accelerator Center. No funds are provided for Project 98–D–126, Accelerator Production of Tritium.

The President's National Energy Policy of May 2001 acknowledged the potential of reprocessing and transmutation technologies to reduce the quantity and long-term toxicity of spent nuclear fuel, and recommended further consideration of such technologies. The Advanced Accelerator Applications program will provide the technical information to support a future policy decision on these options.

The Department is directed to prepare a report for Congress by May 1, 2002, providing a comparison of the chemical and pyro-reprocessing, accelerator-driven transmutation, and fast reactor transmutation alternatives, fully disclosing all waste streams and estimating the life-cycle costs to construct, operate, and decommission and decontaminate all necessary facilities. The Department should also compare the proliferation resistance of the various technologies. The baseline for all comparisons should be the once-through fuel cycle as presently used in the United States, and the amount of spent nuclear fuel presently scheduled for disposal in the geologic repository. The conferees expect this report to present the Department's strategy for siting the new processing and disposal facilities that would be required for the various reprocessing and transmutation alternatives, again assuming a capacity sufficient to process the amount of spent fuel presently scheduled for geologic disposal. The conferees encourage the participation of international collaborators, industrial partners, and U.S. universities in this effort.

INDEPENDENT OVERSIGHT AND PERFORMANCE ASSURANCE

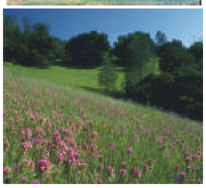
The conference agreement provides $14,904,000, the same as the budget request, for the independent oversight and performance assurance program. The conferees are aware that additional duties for environmental oversight have been assigned to this office and expect the Department to submit a reprogramming to transfer an estimated $7,000,000 to support these oversight activities which have been funded previously in the environment, safety and health program.

ENVIRONMENT, SAFETY AND HEALTH (DEFENSE)

The conference agreement provides $117,688,000 for defense-related environment, safety and health activities. From within available funds, $53,438,000 is provided for health effects studies and $13,500,000 for the Radiation Effects Research Foundation, the same as the budget request. The conferees have provided $5,000,000 to continue a program at the University of Nevada-Las Vegas for Department-wide management of electronic records; $1,750,000 for the University of Louisville and the University of Kentucky to perform epidemiological studies of workers; and $1,000,000 for health studies of workers at the Iowa Army Ammunition Plant.

The U.S. government is currently renegotiating its diplomatic, defense, and economic relationship with the Government of the Republic of the Marshall Islands (RMI). The conferees urge the U.S. government to provide a single, combined package of assistance to support the medical and public health infrastructure needs of the Marshall Islands and believe that the negotiations should include discussion of the transition of the environmental monitoring program to the RMI.





Report to Congress

on

Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research

Appendix B

Generation IV International Forum: Update
October 2002

Summary

The ten member countries of the Generation IV International Forum (GIF) have selected six next generation nuclear energy system concepts, known as Gen IV, to be the focus for collaborative research and development. The GIF, an international collective dedicated to the development by 2030, of the next generation of nuclear reactor and fuel cycle technologies, was announced by US Secretary of Energy, Spencer Abraham, on July 23, 2001, following a meeting of the GIF Policy Group. The member countries of the GIF are: Argentina, Brazil, Canada, France, Japan, Republic of Korea, Republic of South Africa, Switzerland, United Kingdom, and the United States.

The six Gen IV systems were selected by GIF with the help of leading international experts because of their significant potential to advance the sustainability, safety, economics and proliferation resistance of future nuclear systems. As well as electricity generation, the plants offer potential for the generation of hydrogen from water for use in transport and for water desalination. All are considered deployable by at least 2030, with some possibly available as early as 2020. The concepts include a sodium liquid metal-cooled reactor, very high temperature reactor, supercritical water-cooled reactor, lead-alloy-cooled reactor, gas-cooled fast reactor, and molten salt reactor.

Generation IV Technology Goals

The six Generation IV systems selected by the Generation IV International Forum (GIF) countries meet challenging technology goals such as sustainability, economics, safety and reliability, and proliferation resistance and physical protection. By striving to meet the technology goals, new nuclear systems can achieve a number of long-term benefits that will help nuclear energy play an essential role worldwide.

Sustainable Nuclear Energy

Sustainability is the ability to meet the needs of the present generation while enhancing the ability of future generations to meet society's needs indefinitely into the future. The benefits of meeting sustainability goals include:

- Having a positive impact on the environment through the displacement of polluting energy and transportation sources by nuclear electricity generation and nuclear-produced hydrogen;
- Allowing geologic waste repositories to accept the waste of many more plant-years of nuclear plant operation through substantial reduction in the amount of wastes and their decay heat;
- Greatly simplifying the scientific analysis and demonstration of safe repository performance for very long time periods (beyond 1000 years), by a large reduction in the lifetime and toxicity of the residual radioactive wastes sent to repositories for final geologic disposal;
- Extending the nuclear fuel supply into future centuries by recycling used fuel to recover its energy content, and by converting ^{238}U to new fuel.

Competitive Nuclear Energy

Economic goals broadly consider competitive costs and financial risks of nuclear energy systems. The benefits of meeting economic goals include:

- Achieving economic life-cycle and energy production costs through a number of innovative advances in plant and fuel cycle efficiency, design simplifications, and plant sizes;
- Reducing economic risk to nuclear projects through innovative advances that may be possible with the development of plants built using innovative fabrication and construction techniques, and modular plants;
- Allowing the distributed production of hydrogen, fresh water, district heating, and other energy products to be produced where they are needed.

Safe and Reliable Systems

Safe and reliable operation of nuclear systems is an essential priority in the development of next-generation systems. Goals broadly consider safe and reliable operation, improved accident management and minimization of consequences, investment protection, and reduced need for off-site emergency response. The benefit of meeting these goals includes:

- Increasing the use of inherent safety features, robust designs, and transparent safety features that can be understood by nonexperts;
- Enhancing public confidence in the safety of nuclear energy.

Proliferation Resistance and Physical Protection

Proliferation resistance and physical protection consider means for safeguarding nuclear material and nuclear facilities. The benefits of meeting these goals include:

- Providing continued effective proliferation resistance of nuclear energy systems through the increased use of intrinsic barriers and extrinsic safeguards;
- Increasing physical protection against terrorism by increasing the robustness of new facilities.

Generation IV Nuclear Energy Systems

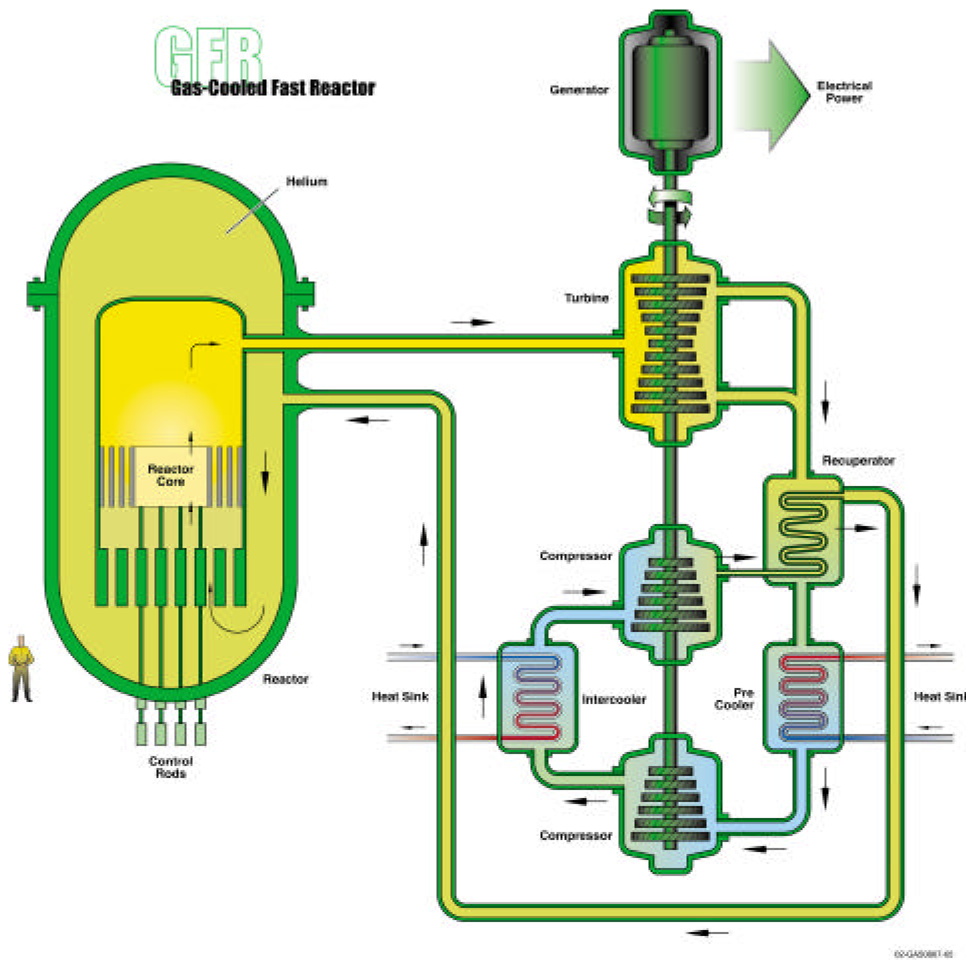
Generation IV nuclear energy systems comprise the nuclear reactor and its energy conversion systems, as well as the necessary facilities for the entire fuel cycle, from ore extraction to final waste disposal. The following six systems, listed alphabetically, were selected as the most promising Generation IV concepts by the GIF:

Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

GFR – Gas-Cooled Fast Reactor System

The GFR system features a fast-neutron-spectrum helium-cooled reactor [shown below] and closed fuel cycle. Like thermal-spectrum helium-cooled reactors, the high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high efficiency. The reference reactor is a 288-MWe helium-cooled system operating with an outlet temperature of 850°C using a direct Brayton cycle gas turbine for high thermal efficiency. Several fuel forms are candidates that hold the potential to operate at very high temperatures and to ensure an excellent retention of fission products: composite ceramic fuel, advanced fuel particles, or ceramic clad elements of actinide compounds. Core configurations may be based on prismatic blocks, pin- or plate-based fuel assemblies. The GFR reference has an integrated, on-site spent fuel treatment and refabrication plant.

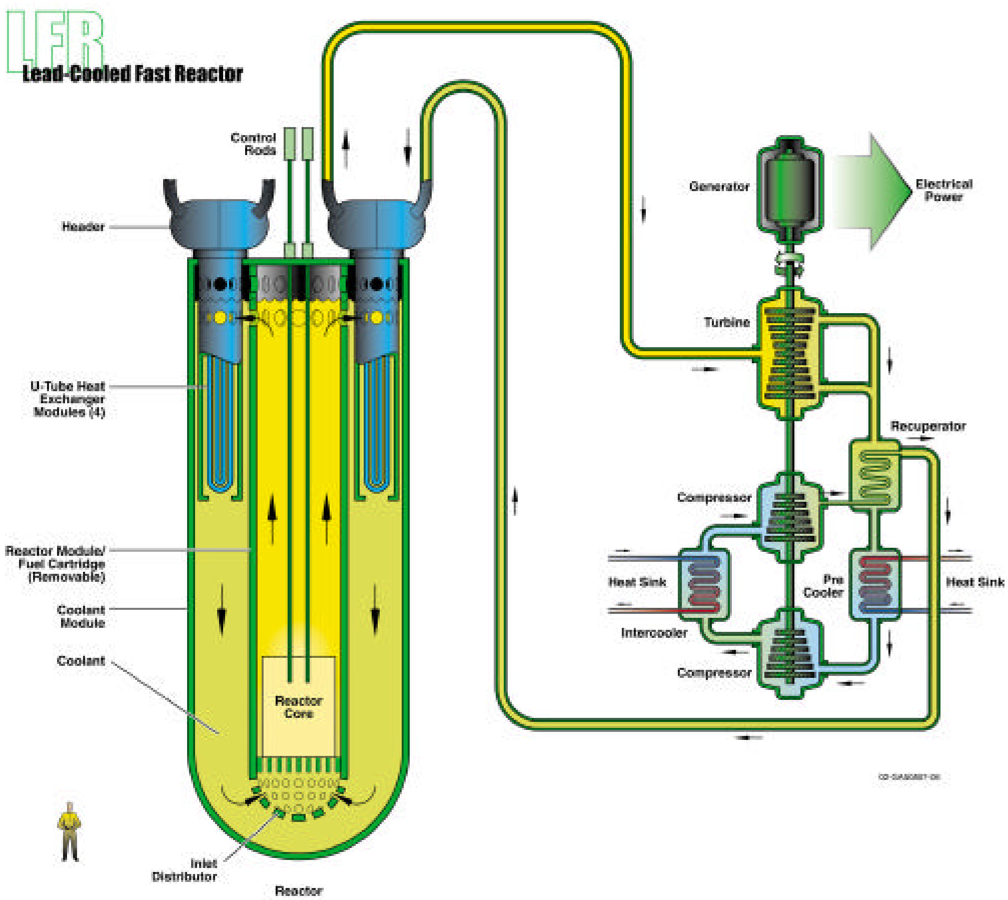
The GFR uses a direct-cycle helium turbine for electricity generation, or can optionally use its process heat for thermochemical production of hydrogen. Through the combination of a fast spectrum and full recycle of actinides, the GFR minimizes the production of long-lived radioactive waste. The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum gas reactors with once-through fuel cycles.



LFR – Lead-Cooled Fast Reactor System

The LFR system features a fast-spectrum lead or lead/bismuth eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The system has a full actinide recycle fuel cycle with central or regional fuel cycle facilities. Options include a range of plant ratings, including a battery of 50-150 MWe [shown below] that features a very long refueling interval, a modular system rated at 300-400 MWe, and a large monolithic plant option at 1200 MWe. The term *battery* refers to the long-life, factory fabricated core, not to any provision for electrochemical energy conversion. The fuel is metal or nitride-based, containing fertile uranium and transuranics. The LFR is cooled by natural convection with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C with advanced materials. The higher temperature enables the production of hydrogen by thermochemical processes.

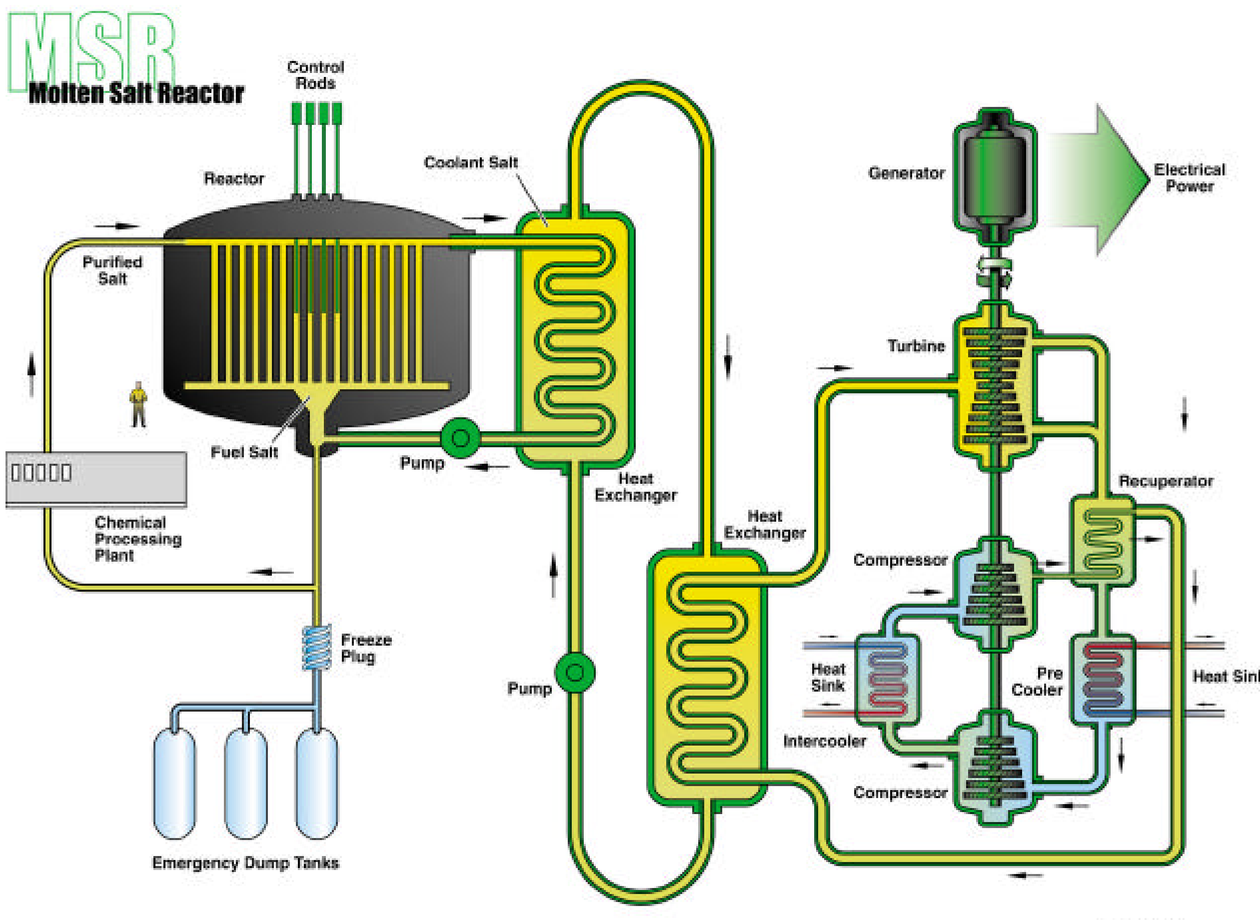
The LFR battery is a small factory-built turnkey plant operating on a closed fuel cycle with very long refueling interval (15 to 20 years) cassette core or replaceable reactor module. Its features are designed to meet market opportunities for electricity production on small grids, and for developing countries who may not wish to deploy an indigenous fuel cycle infrastructure to support their nuclear energy systems. The battery system is designed for distributed generation of electricity and other energy products, including hydrogen and potable water.



MSR – Molten Salt Reactor System

The MSR system produces fission power in a circulating molten salt fuel mixture with an epithermal-spectrum reactor [shown below] and a full actinide recycle fuel cycle. In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium and uranium fluorides. The molten salt fuel flows through graphite core channels, producing an epithermal spectrum. The heat generated in the molten salt is transferred to a secondary coolant system through an intermediate heat exchanger, and then through a tertiary heat exchanger to the power conversion system. The reference plant has a power level of 1000 MWe. The system has a coolant outlet temperature of 700°C, possibly ranging up to 800°C, affording improved thermal efficiency.

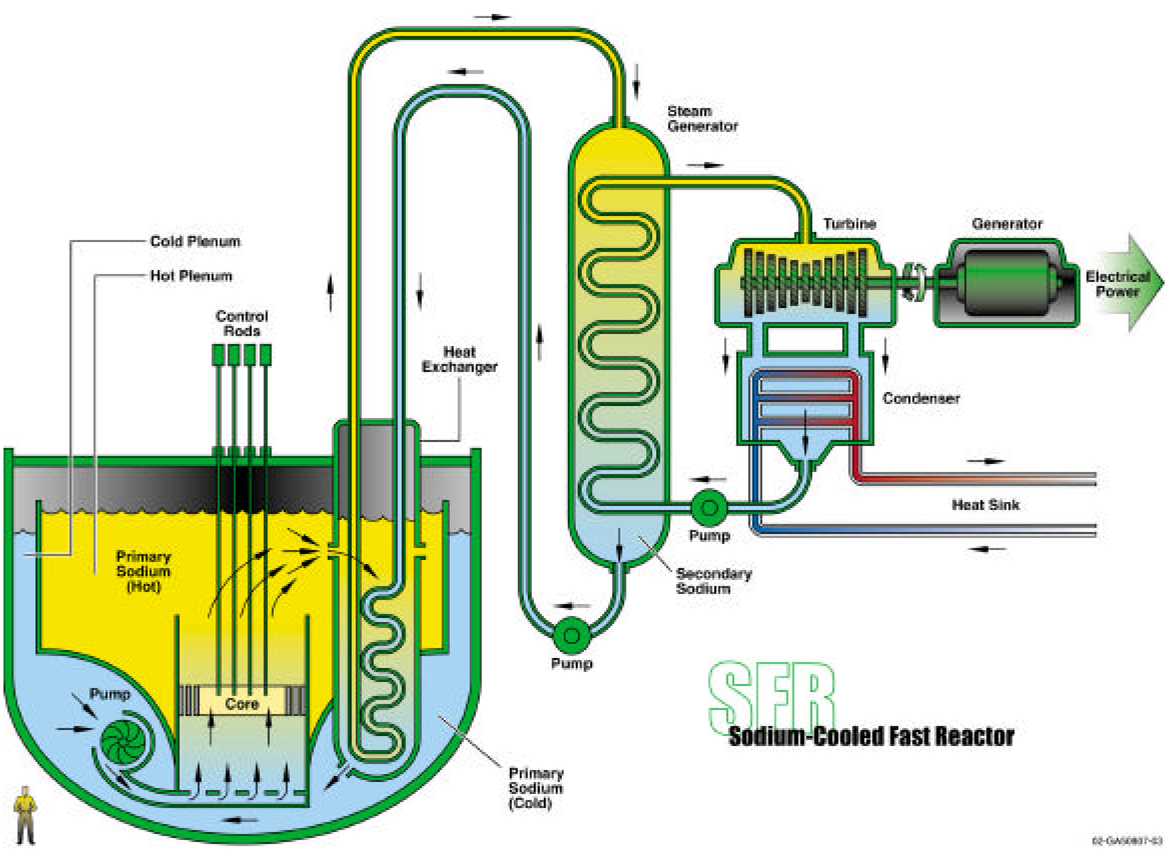
The closed fuel cycle can be tailored to the efficient burnup of plutonium and minor actinides. The MSR's liquid fuel allows addition of actinides such as plutonium and avoids the need for fuel fabrication. Actinides and most fission products form fluorides in the liquid coolant. Molten fluoride salts have excellent heat transfer characteristics and a very low vapor pressure, which reduce stresses on the vessel and piping.



SFR – Sodium-Cooled Fast Reactor System

The SFR system features a fast-spectrum sodium-cooled reactor [shown below] and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The fuel cycle employs full actinide recycle with two major options: One is an intermediate size (150 to 500 MWe) sodium-cooled reactor with a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities integrated with the reactor. The second is a medium to large (500 to 1500 MWe) sodium-cooled reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550°C for both.

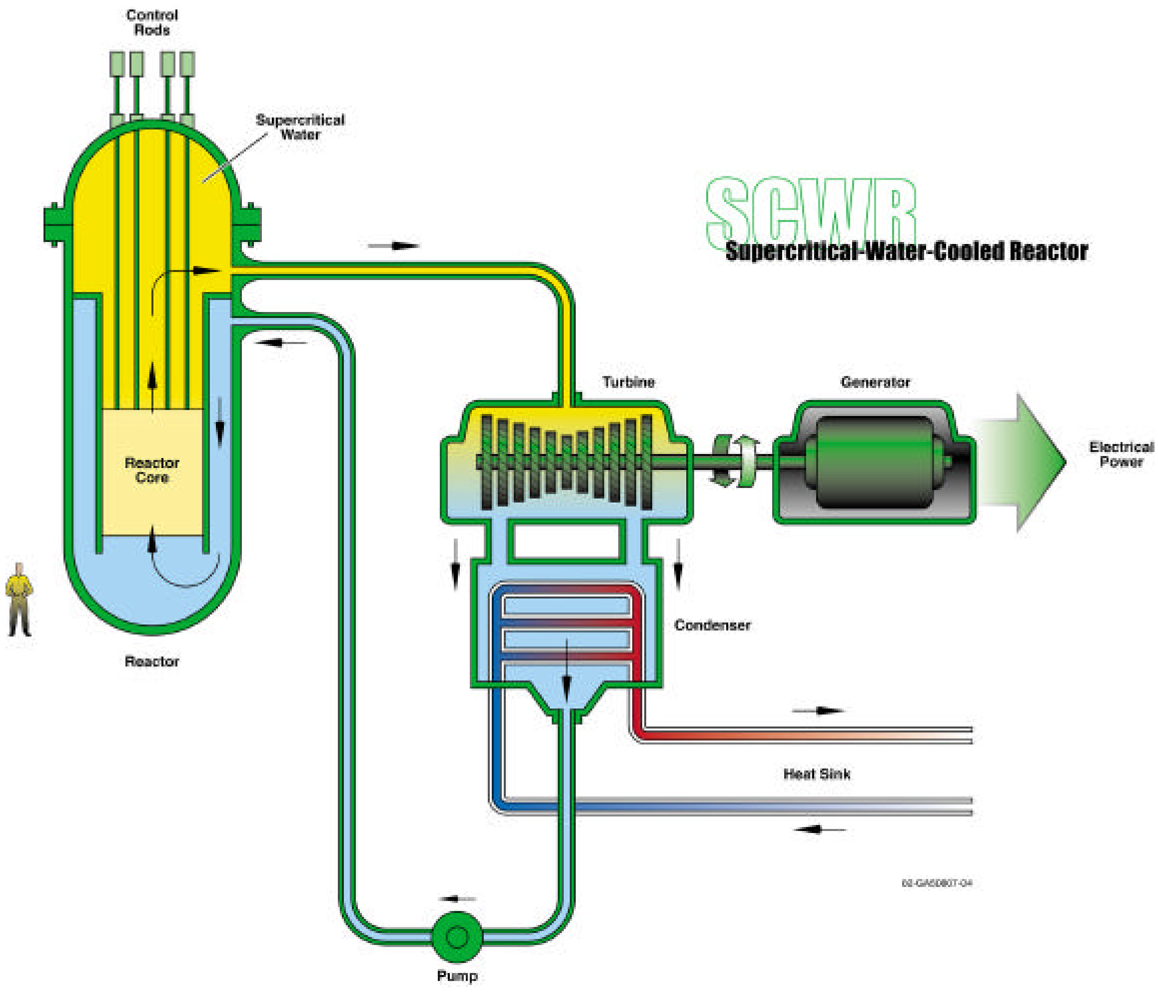
The SFR is designed for management of high-level wastes and, in particular, management of plutonium and other actinides. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the water and steam in the power plant. With innovations to reduce capital cost, the SFR can serve markets for electricity. The SFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum reactors with once-through fuel cycles.



SCWR – Supercritical-Water-Cooled Reactor System

The SCWR system is a high-temperature, high-pressure water-cooled reactor [shown below] that operates above the thermodynamic critical point of water (374°C, 22.1 MPa or 705°F, 3208 psia). The supercritical water coolant enables a thermal efficiency about one-third higher than current light water reactors, as well as simplifications in the balance of plant. The balance of plant is considerably simplified because the coolant does not change phase in the reactor and is directly coupled to the energy conversion equipment. The reference system is 1700 MWe with an operating pressure of 25 MPa, and a reactor outlet temperature of 510°C, possibly ranging up to 550°C. The fuel is uranium oxide. Passive safety features are incorporated similar to those of simplified boiling water reactors.

The SCWR system is primarily designed for efficient electricity production, with an option for actinide management based on two options in the core design: the SCWR may have a thermal or fast-spectrum. Thus, the system offers two fuel cycle options: the first is an open cycle with a thermal-spectrum reactor; the second is a closed cycle with a fast- spectrum reactor and full actinide recycle based on advanced aqueous processing at a central location.



VHTR – Very-High-Temperature Reactor System

The VHTR is a graphite-moderated, helium-cooled reactor [shown below] with a once-through uranium fuel cycle. It supplies heat with core outlet temperatures of 1000°C, which enables applications such as hydrogen production or process heat for the petrochemical industry or others. The reference reactor is a 600 MWth core connected to an intermediate heat exchanger to deliver process heat. The reactor core can be a prismatic block core such as the operating Japanese HTTR, or a pebble-bed core such as the operating Chinese HTR-10. For hydrogen production, the system supplies heat that could be used efficiently by the thermochemical iodine-sulfur process.

The VHTR system is designed to be a high-efficiency system that can supply process heat to a broad spectrum of high-temperature and energy-intensive, nonelectric processes. The system may incorporate electricity generating equipment to meet cogeneration needs. The system also has the flexibility to adopt U/Pu fuel cycles and offer enhanced waste minimization. Thus, the VHTR offers a broad range of process heat applications and an option for high efficiency electricity production, while retaining the desirable safety characteristics offered by modular high-temperature gas-cooled reactors.